CENTENNIAL VALLEY ARCTIC GRAYLING ADAPTIVE MANAGEMENT PLAN

DRAFT

1 January 2016

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Introduction

Montana Arctic grayling (grayling) were patchily distributed throughout the Upper Missouri River (UMR) drainage prior to the mid-1850s. This population declined to about 4% of their perceived historic distribution by the 1990s, which led to formal consideration for listing under the Endangered Species Act (USFWS 2014). One of the last populations of indigenous Montana Arctic grayling resides in the Centennial Valley (CV). Arctic grayling were historically distributed among at least a dozen CV streams and three lakes at presumably high abundances (Nelson 1954). Perceived distribution and abundance declined to historic lows sometime between the 1950s and mid-1990s but have since improved (USFWS 2014, MAGWG in press). Currently, most of the grayling population in the CV spawns in Red Rock Creek and spends non-breeding portions of the year in Upper Red Rock Lake (Upper Lake) within Red Rock Lakes National Wildlife Refuge (Refuge). Over the past 70 years numerous hypotheses were posited regarding drivers of the CV Arctic grayling population, including 1) diversion of streams for irrigation or waterfowl management, 2) reduction and alteration of spawning habitat, 3) competition and predation by non-native fishes, and 4) limited winter habitat. Although these hypotheses have been repeatedly proposed to explain population contraction and expansion, drivers of the population remain unclear. Previous and ongoing research has focused on aspects of each hypothesis but has not linked them to demographic responses in grayling, which precludes inference regarding their role as population drivers. Resultantly, the most effective management and conservation approaches for CV grayling remain ambiguous. This plan seeks to elucidate the relative effect of hypothesized drivers of CV grayling abundance to direct future management of this population.

Extensive irrigation occurred from most tributary streams by the early 1900s and complete dewatering of streams for irrigation, especially during periods of drought, likely had a large influence on distribution, abundance, and life history strategies of grayling through time (Deeds and White 1926, Vincent 1962, Randall 1978). Diversion of water from streams on public and private lands has been repeatedly listed as a major threat to grayling in agency reports since 1950. Surface water is still diverted from Red Rock Creek upstream of Upper Lake for irrigation or to benefit migratory birds (USFWS 2009), and dewatering continues to occur on streams that support grayling downstream of Lower Red Rock Lake (FWP unpub. data). However, diversion of CV streams for irrigation constitutes less of a threat to grayling than it did historically. Irrigation diversions that entrained grayling during the mid-1900s on Red Rock and Odell creeks are no longer used. Establishment of minimum instream flow reservations (FWP 1989, Kaeding and Boltz 1999), compact settlement between the Montana Reserved Water Rights Compact Commission and the Refuge (MCA 2000), Refuge acquisition of private lands, and changes in management practices on public and private lands have greatly reduced the threat of irrigation diversion in some Upper and Lower Lake tributaries.

Decline of spawning habitat quantity and suitability resulted from land use changes associated with livestock and water management. Initially used as summer range beginning in 1876, year-round livestock operations quickly became common in the CV; by 1892 21 ranches existed within the present-day Refuge boundary and settlement and grazing was associated with most waters throughout the CV (Vincent 1962, Unthank 1989, Centennial Valley Historical Society 2006). Common impacts of grazing in riparian systems include degradation of woody riparian vegetation and increased fine sediments in the streambed, summer water temperatures, and nutrient levels of streams (see review in Clary and Webster 1989, and citations within). Sedimentation of spawning reaches resulting from grazing has been repeatedly documented in Red Rock, Odell, and Tom creeks and was reported as the primary threat to grayling persistence for much of the 1900s (Vincent 1962, Myers 1977, Mogen 1996). Manipulation and consolidation of flow among channels of Hellroaring Creek to facilitate irrigation causes erosion and sedimentation on reaches of Red Rock Creek upstream of the most heavily used spawning habitat in the CV. Serial impoundment of the Elk Springs Creek watershed has destroyed or isolated historically important spawning habitats. Elk Springs Creek was diverted into Swan Lake as early as 1908, which may have partially fragmented this formerly heavily used spawning tributary. Spawning habitat in upper Elk Springs Creek was fragmented and destroyed by sedimentation resulting from impoundment of Blair Pond in 1912 and McDonald Pond in 1953. Picnic Creek was first impounded to create Widow's Pool in 1900 (Centennial Valley Historical Society 2006), which was expanded into Culver Pond in 1959, and by the downstream Widgeon Pond in 1964 (Gillin 2001). Finally, fragmentation and degradation of spawning tributaries by beaver dams has been suggested to preclude grayling spawning in CV tributaries to varying degrees (Nelson 1954, Unthank 1989). Recent management direction has likely improved grayling spawning habitats in parts of the CV. A combination of Refuge land acquisition and changes in grazing management on public and private lands has ameliorated this threat on most Red Rock lakes' tributaries, although degraded conditions remain on some streams in the lower CV (USFWS 2009). McDonald Pond was converted back into stream beginning in 2009 and plans are in place to remove at least one of the Picnic Creek impoundments to restore connectivity and spawning habitat to Elk Springs Creek (USFWS 2009).

Competition or predation by native (burbot, white suckers) and non-native (Yellowstone cutthroat, rainbow, and brook trout) fishes have been hypothesized to affect CV grayling. Early settlers introduced non-native fishes, followed by decades of agency introductions, largely for recreational fisheries. Stocking of CV waters with rainbow trout (*Oncorhynchus mykiss*) began as early as 1899, followed by brook trout (*Salvelinus fontinalis*) in 1900, and Yellowstone cutthroat trout in 1967 (Randall 1978). Although grayling have persisted with these introduced species in the CV, the degree to which they limit the population remains ambiguous. Early work documented predation of grayling eggs and age-0 grayling by brook trout (Nelson 1954), and more recent work corroborated grayling egg predation (Katzman 1998). Predation on age-0 and age-1 grayling by cutthroat trout has not been documented (Nelson 1954, Katzman 1998, USFWS unpubl. data), but effective sampling has not occurred during winter when predation may be most likely due to lower habitat and food availability (Katzman 1998, USFWS unpubl. data). Recent stable isotope analysis identified a greater contribution of fish to the late-winter diet of cutthroat trout in Upper Lake, although no predation of grayling was observed during analysis of stomach contents (USFWS unpubl. data). Stable isotope analysis also indicated that dietary overlap between Yellowstone cutthroat <450 mm and grayling of all sizes in Upper Lake occurs, although it is not possible to determine whether competition for forage items exists because forage availability data were not collected. Populations of native fishes, such as burbot and white and long nose suckers, were experimentally suppressed at various times between the 1960s and 1980s in Upper Red Rock Lake because of their hypothesized effects on grayling, although the effect of these actions were not evaluated (Skates 1985, Unthank 1989).

Limited winter habitat is another potential driver of observed declines in grayling in the Centennial Valley. Upper Lake is a shallow (typically < 2 m) eutrophic lake that provides the primary winter habitat for grayling in the CV. An early account documented Upper Lake depths >6.1 m (20 ft; Browers 1896, Vincent 1962), although reported maximum depths from the 1950s to present time generally don't exceed 1.8 m (6 ft). The locations where depths of >6 m were measured are unknown and a single core sample of lake substrate suggests that sedimentation rate has not changed in Upper Lake since pre-settlement times, although possible changes in water depths cannot be inferred from this sample (C. Whitlock, pers. comm.). Nonetheless, winter oxygen depletion rates in shallow eutrophic lakes are relatively high (Mathias and Barica 1980), which can lead to high winterkill risk for fish (Barica and Mathias 1979, Fang et al. 2004). Winter hypoxia facilitated by shallow depths and high production of macrophytes presently occurs over large parts of Upper Red Rock Lake during some years (Randall 1978, Gangloff 1996, K. Cutting pers. comm.). During winters where hypoxic conditions were documented (1976, 1994, 2011), dissolved oxygen levels fell below the critical oxygen minima for grayling (1.3–1.7 ppm; Feldmeth and Eriksen 1978) in several areas of the lake (Gangloff 1996). Grayling have persisted in the CV ostensibly under persistent risk of winterkill in Upper Lake; however, the relative significance of winterkill may currently be greater due to lack of connectivity with other Montana Arctic grayling populations, which precludes gene flow and a refounding source for the population.

Ambient conditions during spawning, incubation, and early rearing periods can influence cohort strength and, ultimately, population abundances in fishes in general (Crecco and Savoy 1984, Mills and Mann 1985, Nunn et al. 2003, Warren et al. 2009) and grayling in particular (Clark 1992, Deegan et al. 1999). There are contrasting theoretically ideal hydrologic scenarios for adult grayling and eggs or fry. High flows and low temperatures are physiologically favorable for adults and create good spawning habitat (i.e., exposed, flushed gravel beds) whereas low or stable, warm flows are typically better for survival of eggs or fry (Clark 1992, Deegan et al. 1999). The latter of these two scenarios is hypothesized to set year class strength between spawning and approximately five weeks following emergence. An ideal hydrograph for all life stages would be good flows prior to spawning and a rapidly declining hydrograph and increase in stream temperatures or stable, spring-like hydrograph following spawning. Conversely, any peaks in the hydrograph or cool temperatures post-spawning are believed to reduce survival probabilities of eggs or fry. It is presently unknown whether these factors are a driver of CV grayling population and, if so, the magnitude of their influence relative to the aforementioned stressors. An improved understanding of the relative effect of hypothesized natural and anthropogenic population drivers is necessary to assess the benefits of implementing future management actions.

Uncertainty regarding the cause(s) of the observed decline and recent expansion of grayling in the CV remains after greater than 70 years of study and debate. Determining the cause of previous population declines, *per se*, is not the primary issue of grayling conservation and management – finding an effective strategy to achieve population goals and prevent future declines is. In an effort to accomplish this, an adaptive management (AM) approach is being undertaken (Walters 1986). The Arctic grayling AM plan will embrace existing uncertainty regarding drivers of the grayling population in the CV, provide further understanding of important limiting factors, and help guide management actions toward those that will have the most direct benefit to grayling.

Study Area

The Centennial Valley of southwestern Montana is a high-elevation (ca. 2013 m) valley dominated by sagebrush steppe comprising *Artemisia* spp. shrub overstory and native bunchgrass understory (e.g., *Festuca* spp., *Nasella* spp., and *Hesperostipa* spp.). The valley is bounded on the north by the north-south trending Gravelly and Snowcrest mountain ranges and on the south by the east-west trending Centennial Mountains. Extensive wetlands exist throughout the CV, including a large shallow lake/wetland complex encompassed by Red Rock Lakes National Wildlife Refuge (Figure 1). The complex comprises Upper Red Rock, Lower Red Rock, and Swan lakes and associated palustrine emergent marsh dominated by seasonally-flooded sedge (*Carex* spp.). The complex is a remnant of Pleistocene Lake Centennial, a prehistoric lake that was believed to have formerly covered the valley floor to a depth of ca. 20 m (Mumma 2010). Upper Lake, the largest and deepest of the lakes, is ca. 1198 ha with a maximum depth of 2 m. The geologic (Sonderegger 1981; Centennial Valley Historical Society 2006), hydrologic (Deeds and White 1926, MTFWP 1989, MCA 2000), and fisheries (Nelson 1952, Randall 1978, Boltz 2000, Oswald et al. 2008) resources and contemporary administrative status (USFWS 2009) within the Centennial Valley are well described elsewhere.

The Centennial Valley includes all tributaries of the Red Rock River and their associated drainages upstream of Lima Dam (Figure 1). Most of the Upper Lake tributaries have their origins to the south along the eastern extent of the Centennial Mountains. Red Rock Creek, the largest of these tributaries, originates at an elevation of 2,562 m and flows north and west ca. 21 km to the northeast shore of Upper Lake. Mean annual discharge for Red Rock Creek during 1997–2012 was 48.2 cubic feet sec^{-1} (cfs) (SD = 17.3). Annual peak daily discharge varied between 16 May and 26 June during the period 1997–2004, with peak mean-daily discharge varying from 98 cfs (28 May 2000) to 293 cfs (10 June 1997). Elk Springs Creek originates from a series of springs south of Elk Lake and flows southwest, entering Swan Lake along the northeast shore; the latter drains into Upper Lake to the south. Annual peak daily discharge of Elk Springs Creek upstream of Picnic Creek varied between 30 April and 22 October during the period 1999–2004, with discharge ranging from 10.9 cfs in 1999 to 7.6 cfs in 2004. A more recent discharge of 16.5 cfs was measured 7 June 2011, near the confluence with Picnic Creek. Picnic Creek contributes an additional 10.5 cfs at this junction, resulting in a combined discharge of 27 cfs in Elk Springs Creek as it flows toward Swan Lake. Red Rock River exits Upper Lake in the northwest corner, carrying water through the River Marsh and into the northwestern corner of Lower Lake. Red Rock River continues westward through the outlet of Lower Lake, ca. 1.5 km west of where it enters the lake, leaving the CV near Lima, MT after passing through the 8 mile long Lima Reservoir. Long Creek enters the Red Rock River 17 km downstream of the Lower Lake outlet and just upstream of Lima Reservoir. Peak discharge of Long Creek varied between 48 and 265 cfs during 1960–1964; earliest and latest peak discharge during this period was 6 April 1960 and 14 June 1963. West Creek is the downstream-most spawning tributary in the CV and enters Red Rock River in the headwaters of Lima Reservoir. Peak discharge for West Creek was about 29 cfs and base flows were between 6 and 3 cfs in 2015.

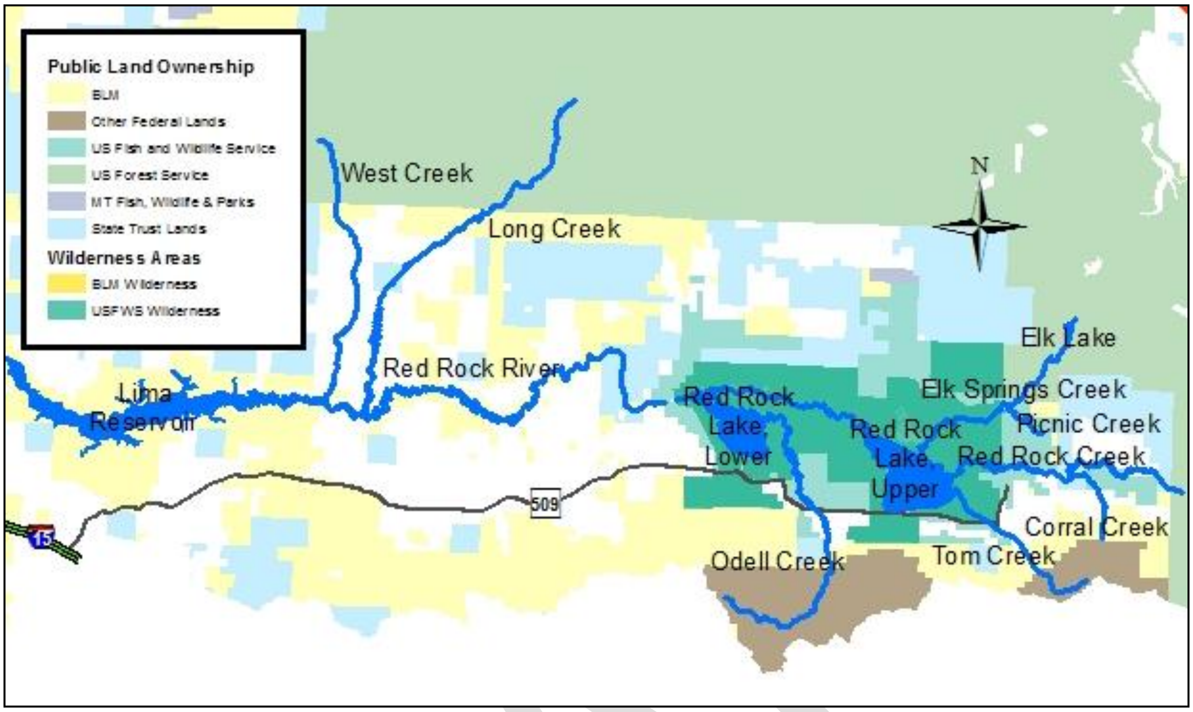

Figure 1. Arctic grayling adaptive management plan study area within the Centennial Valley of southwestern Montana.

Adaptive Management Plan Approach

The central tenet of the AM approach is that systemic knowledge is gained through a series of well-designed ecological experiments. These experiments are *de facto* hypothesis tests that iteratively seek to manipulate an ecological system by altering hypothesized limiting factors and measuring the response. The manipulations in these experiments are the suite of possible management actions available to ameliorate limiting factors and achieve management or conservation goals for CV grayling. Comparison of relative population responses among hypothesis tests defines the most effective management actions to achieve population goals. Thus, this plan describes how each implemented management action should be structured, timed, and evaluated to serve as a test of a hypothesized population driver for CV grayling. This plan is unique from all previous research and management efforts in the CV because it seeks to determine which hypothesized limiting factors are actual population drivers by linking them to grayling demographic rates.

The AM Plan is a tool intended to facilitate achievement of CV grayling management and conservation goals in perpetuity. The ultimate conservation goal for Montana Arctic grayling is described in the Upper Missouri River Drainage Arctic grayling Conservation and Restoration Plan (MAGWG, in press) as follows:

Ensure the long-term, self-sustaining persistence of Arctic Grayling in the upper Missouri River Basin by maintaining the geographic distribution, abundance, and genetic diversity of remaining aboriginal populations, and where feasible, reestablishing populations in suitable habitats within their historic range. Self-sustaining persistence occurs when, after 5 generations, Arctic Grayling populations exhibit a stable or increasing trend in effective number or breeders (Nb) and the effective population size (Ne) is greater than 50.

Accordingly, the CV Arctic grayling working group, comprising agencies and NGOs with direct fish or land management responsibility, developed the following objectives to meet the species-wide population goal within the CV:

1) Conserve existing Centennial Valley Arctic grayling genetic diversity.
2) Establish or maintain Arctic grayling spawning or refugia in at least two tributaries up and downstream of Upper Red Rock Lake and connectivity among tributaries.
3) Increase suitable conditions for the Upper Red Rock Lake Arctic grayling population.

This AM plan will be most effective if it is directly responsive to the CV grayling population goal and its objectives. Although goals related to Arctic grayling populations exist in a variety of agency and area-specific documents, they are subservient to the species-wide goal and can be best viewed as strategies to achieve it. This plan will not supersede existing policies, plans, agreements, or efforts with respect to established goals and objectives of the various involved agencies. The AM plan is an opportunity to collectively learn from ongoing work and most efficiently achieve broader CV grayling population goals.

AM Plan Scale

There are several scales at which the project could proceed, ranging from the CV down to exclusive focus on a single stream or population segment. Exclusively targeting one stream is primarily beneficial for logistical and economic reasons including 1) personnel time would not be divided among several streams for sampling, which would likely result in less precise estimates of response and predictors, 2) a broader suite of predictors could be measured, and 3) sampling would be more economical. Possible drawbacks include 1) it may take longer to separate out the influence of confounded predictors (e.g., if spring conditions and winter conditions increase or decrease together, i.e., covary, it will be difficult to determine the relative role of each in observed changes of grayling abundance), 2) ongoing work within the CV would not be integrated, losing an opportunity to include other treatments (i.e., habitat restoration in Long, West, and Elk Springs creeks and grayling restoration in Elk Springs Creek),and 3) there would be no spatial replication, which reduces the efficiency of learning. Ultimately the most important consideration is the overarching intent of the AM project - to efficiently achieve CV Arctic grayling population goals by identifying the most effective management strategies. Because CV grayling population goals pertain to the entire valley, the AM plan will be most useful by adopting a similar scale. However, applying equal monitoring effort and achieving similar data quality throughout the CV is impractical so some optimization of treatments and monitoring approach will be required.

Implementation of this project will be CV-wide but will vary among streams. Taking a CV-wide approach will include upper valley (Red Rock and Elk Springs creeks, Upper Red Rock Lake) and lower valley (Long and West creeks, Lima Reservoir) water bodies. Level of knowledge about the graying population, availability and quality of existing data, cost of monitoring, and conservation importance differs between the upper and lower valley making it impractical to implement similar monitoring and analysis regimes on all streams. Because the majority of the CV grayling population inhabits the Upper Lake and Red Rock Creek conservation, monitoring, and research focus has traditionally been placed in the upper valley and collection of additional high quality data can occur efficiently there relative to the lower valley. As such, primary emphasis will be placed on upper valley streams (Red Rock and Elk Springs creeks) to maximize data quality, collection efficiency, and analysis options. Lower valley streams (Long and West creeks) will also be included in this plan but data collection and analysis will necessarily be less rigorous than for upper valley streams. Although asymmetrical data collection among streams will preclude direct comparison between hypothesis tests in the upper and lower valley, general inference that is applicable throughout the CV will be possible.

Although there isn't a true control for this work this suite of streams provides 1) a spring creek (Elk Springs) that will provide a constant-flow system relative to the other three creeks, and 2) a spawning population presumably not wintering in Upper Red Rock Lake (Long and West creeks). Treatments may still be confounded and there is little replication in this scenario, with potential management actions including grayling and habitat restoration in Elk Springs Creek, habitat restoration and instream flow conservation in Long and West creeks, and improved connectivity and fish removals in shared winter habitat for fish spawning in Elk Springs and Red Rock creeks. However, given current grayling distribution and management focus in the CV, this set of four streams provides the best opportunity for both efficient learning and achievement of management goals.

Hypothesis Definition

Identifying factors that influence attainment of population goals is an essential component of effective management. When uncertainty about which factors are most influential to a population exists this process entails developing and testing competing hypotheses about ecological systems. The following hypotheses have been repeatedly suggested over the past 70 years to explain CV Arctic grayling distribution and abundance.

1) Dewatering of streams for irrigation is the primary driver of the CV Arctic grayling population.

2) Quality and quantity of tributary spawning habitat is the primary driver of the CV Arctic grayling population.

3) Predation by adult Yellowstone cutthroat trout is the primary driver of the CV Arctic grayling population.

4) Quality and quantity of overwinter habitat in Upper Red Rock Lake is the primary driver of the CV Arctic grayling population.

5) Ambient conditions during the spawning and early rearing period are the primary driver of the CV Arctic grayling population.

Anecdotal or observational data that both support and refute each hypothesis presently exists, creating ambiguity regarding true population drivers. Our goal is to disentangle the ambiguity by conducting focused empirical tests of these hypotheses and ultimately determine to what degree each characterizes the CV Arctic grayling population. These results will dictate the most effective management approach to achieve CV grayling population goals.

Limiting Factors and Management Actions

Effective hypothesis testing requires placing population drivers in the context of limiting factors. Limiting factors are demographic components that constrain population growth of a species. Identifying limiting factors, perceived and documented, clarifies uncertainty regarding drivers of the CV Arctic grayling population and the potential management actions that address them, including monitoring approaches required to link the two together. For example, winter survival could be a limiting factor if it was low enough to prevent population growth in grayling. Habitat conditions or presence of non-native fish could be primary causes (i.e., population drivers) for low winter survival. Each would have specific management actions that could be taken to mitigate the conditions that lead to low survival. Based on existing competing hypotheses, we’ve identified five potential limiting factors for grayling, possible causes, and mitigating management actions (Table 1). All the identified limiting factors are potential, i.e. not documented, at this point.

Implementation of management actions is the mechanism by which hypotheses about limiting factors will be tested. Management actions identified in Table 1 include both current (i.e., removal and harvest of non-native fish, restoration and grazing management of tributaries) and potential (dredging or aeration of Upper Red Rock Lake, removal of Widgeon and/or Culver ponds, habitat and connectivity restoration in Elk Springs and Red Rock creeks, restoration and grazing management of tributaries, in-stream flow conservation) systemic manipulations. Management actions to test every potential population driver or their associated limiting factors are not planned at this time. If the suite management actions created for the initial hypothesis tests described in this plan do not address true limiting factors then Table 1 will be revisited to formulate new hypothesis tests and management actions.

Table 1. Hypothesized limiting factors for Arctic grayling in the Centennial Valley watershed, Montana. Possible causes and potential mitigating actions to address each limiting factor are also provided.

Limiting Factor	Population Driver	Management Action
Egg survival	Spawning habitat availability	Restoration
		Grazing management
		Provide connectivity
	Spring hydrology	None
Age 0 survival (summer)	Low stream flows	In-stream flow conservation
	Sedimentation	Restoration
		Grazing management
	Fragmentation	Provide connectivity
	Predation or competition	Non-native fish suppression
	Spring hydrology	None
Age 0 survival (winter)	Low dissolved O_2 levels	TBD if necessary
	Predation or competition	Non-native fish suppression
Age 1 survival	Low stream flows	In-stream flow conservation
	Low dissolved O_2 levels	TBD if necessary
	Predation or competition	Non-native fishsuppression
	Fragmentation	Provide connectivity
Age 2+ survival	Low stream flows	In-stream flow conservation
	Low dissolved O_2 levels	TBD if necessary
	Fragmentation	Provide connectivity
	High temperatures	Restoration

Hypothesis Tests

Structure, timing, duration, and evaluation of each implemented management action must be carefully defined to ensure it provides the intended test of an established hypothesis (Table 2). For example, each implemented management action (i.e., hypothesis test) should be temporally or spatially isolated from other management actions to reduce the likelihood of confounded results, a common response variable must be defined to allow meaningful discrimination among hypotheses, and each hypothesis test should be of adequate duration for a response to occur and be observed. We expect that adequate spatial isolation exists to concurrently test hypotheses that influence the upper (i.e., Upper Red Rock Lake and Red Rock and Elk Springs creeks) and lower (i.e., Long and West creeks) valley populations; however, temporal isolation is required among hypothesis tests within each population segment. The minimum duration of each hypothesis test will be five years, which is the approximate generational periodicity of Arctic grayling and the soonest a response to a management action can be detected. Sequence of hypothesis tests will be determined by already planned management actions (Table 2).

Table 2. Hypothesis testing schedule and approach.

Hypothesis	Management Action	Valley segment	Water Body	Timeframe
YCT competition or predation	YCT suppression	Upper	Red Rock Creek, Upper Lake	2013-2017
Spawning habitat	Connectivity, restoration	Upper	Red Rock and Elk Springs creeks	2018-2022
Overwinter habitat	Unknown	Upper	Upper Lake	TBD if necessary
Flows and spawning habitat	CCAA	Lower	Long and West creeks	2017-2021

Within each valley segment, management actions will be linked to a common response variable by hypothesis-specific models of system dynamics. Each model is responsive to the demographic effects a given management action is hypothesized to have on CV Arctic grayling. Description of management actions and demographic rates associated with each hypothesis are as follows:

1) Dewatering of streams for irrigation is the primary driver of the CV Arctic grayling population.

Diversion of water for irrigation has reduced in-stream flows in Long and West creeks. Management actions will improve in-stream flows. These management actions are hypothesized to influence abundances of spawning Arctic grayling by improving survival of all life stages that reside in Long and West creeks.

2) Quality and quantity of tributary spawning habitat is the primary driver of the CV Arctic grayling population.

Spawning habitat in upper Red Rock Creek has been degraded by consolidation of channels on an alluvial fan into a single channel and in Elk Springs Creek by fragmentation, impoundment, and sedimentation. Beaver activity may have further reduced availability and connectivity of suitable spawning habitat in both streams. Management actions on Red Rock Creek will reduce erosion and sedimentation and restore floodplain connectivity and natural processes of habitat formation to upper reaches. Management actions on Elk Springs Creek will restore connectivity and improve spawning habitat quality. All beaver dams on Red Rock and Elk Springs creeks will be breached during spawning periods to ensure all suitable spawning habitats are accessible. Management actions on Long Creek will reduce erosion and sedimentation and restore floodplain connectivity and natural processes of habitat formation. These management actions are hypothesized to influence abundances of spawning Arctic grayling by improving egg and fry survival.

3) Predation by adult Yellowstone cutthroat trout is the primary driver of the CV Arctic grayling population.

Non-native Yellowstone cutthroat may prey upon juvenile grayling in Upper Red Rock Lake. Management actions will suppress adult Yellowstone cutthroat trout abundances by removing spawning fish from Red Rock Creek via liberalized recreational angling regulations (20 fish daily and in possession) and an agency-operated weir. These management actions are hypothesized to influence abundances of spawning Arctic grayling by improving age 0 and age 1 survival.

4) Quality and quantity of overwinter habitat in Upper Red Rock Lake is the primary driver of the CV Arctic grayling population.

It is presently unclear whether refuge from potentially lethal dissolved oxygen concentrations exists or what levels of dissolved oxygen are lethal to CV Arctic grayling in Upper Red Rock Lake. Ongoing research is investigating both factors and test of this hypothesis is pending those results. Low dissolved oxygen concentrations are hypothesized to influence abundances of spawning Arctic grayling by affecting survival of all ages of Arctic grayling overwintering in Upper Lake.

5) Ambient conditions during the spawning and early rearing period are the primary driver of the CV Arctic grayling population.

Ambient hydrology and temperature during spawning and rearing periods may set CV Arctic grayling year class strength. No management actions are associated with this hypothesis; ambient conditions will be monitored to assess whether they best predict abundances of spawning Arctic grayling. Discharge and temperature are hypothesized to influence abundances of spawning Arctic grayling by affecting egg and fry survival.

Model Comparison

Learning in adaptive management is the reduction of structural uncertainty, i.e., identifying the most likely hypothesis regarding how a system responds to management actions. This is accomplished through discrimination of competing models that represent different hypotheses of system dynamics. To discriminate among models, every year each model will be fitted to the existing data and predictions of grayling abundance will be generated. These model-based predictions will then be compared to maximum likelihood estimates for Arctic grayling derived from mark-recapture sampling for that year, with the model that makes the most accurate prediction receiving more 'weight' than the others. Finally, each model will be updated with the data collected that year and the process repeated. For example, each of the models described below will be used to annually predict Arctic grayling abundance during spawning. This prediction will be compared to the number of spawning grayling estimated from monitoring data. This process is repeatedly annually; ideally a single model will consistently predict better than the others, resulting in incrementally increasing model weight (i.e., increasing confidence that the model is the best descriptor of system dynamics). If a single model does not separate from the other competing models the hypotheses will need to be revisited and new hypotheses and/or models created. Lower Valley models will be compared similarly, although a different response variable will be used (see below).

Model weights will be calculated annually using Baye's formula, which allows adding new information (i.e., an updated comparison of predicted and observed grayling abundances) to existing information (i.e., existing model weights based on prior comparisons of predicted and observed grayling abundances). The model weight of model i in year $t+1$ given the observed data (i.e., response), $p_{i,t+1}$, is calculated as the prior model weight ($p_t(model_i)$) multiplied by the probability of the observed data in $t+1$ given model i ($P(response_{t+1}|model_i)$), divided by the total probability of all the models given the observed data ($\sum_{j=1}^{n} p_t\big(model_j\big)P(response_{t+1}|model_j)$),

$$p_{i,t+1} = (model_i|response_{t+1}) = \frac{p_t(model_i)P(response_{t+1}|model_i)}{\sum_{j=1}^{n} p_t\big(model_j\big)P(response_{t+1}|model_j)} \qquad (22)$$

Population of Interest

A succinct and precise definition of the population of interest is essential to success in developing models of system dynamics and appropriate monitoring. In the context of this plan the population of interest is the response variable for competing models of system dynamics. A metric describing the number of spawning grayling per stream is the population of interest for the AM plan. Estimated census abundance of spawning grayling will be the response variable for fish using the upper valley. The population of interest in the lower valley will be a genetic metric relevant to estimated annual (number of breeders, Nb) or generational (effective population size, Ne) abundance of successful spawners. Genetic metrics will also be evaluated in Upper Red Rock Lake tributaries for the purpose of comparison among population segments and to estimated census population size.

Because different model structure and response variables will be used in the upper and lower valley segments to evaluate hypothesis tests the remainder of the plan will be divided by valley segment.

UPPER VALLEY HYPOTHESIS TEST EVALUATION

Models of System Dynamics

Spawning habitat, non-native fishes, winter habitat, and spring and summer hydrology have all been identified as potentially important drivers of grayling population dynamics in the upper CV. Each of these hypotheses is translated into a model, or set of models, to link hypothesized drivers and limiting factors.

The annual abundance of spawning grayling is the product of demographic rates ranging from adult survival to the number of eggs deposited per female (fecundity) three years prior. All population models for spawning grayling, excluding a null logistic growth model, share a common balance equation that allows prediction of annual abundance as a function of survival and recruitment processes:

$$N_{t+1} = N_t S_t + (F_{t-2}\alpha_{t-2}\beta_{t-2}\gamma_{t-2}\delta_{t-2}\varepsilon_{t-1})\theta_t. \tag{1}$$

The number and survival of adult (i.e., reproductive age) grayling in year t is N_t and S_t, respectively. Assuming recruitment occurs with the age-3 cohort in year t + 1 (i.e., knife-edge recruitment at age-3), the number of potential age-2 recruits in year t is the product of:

F_{t-2} – the number of females in the spawning run in year t – 2,
α_{t-2} – length-specific fecundity rate, year t – 2,
β_{t-2} – probability of an egg being fertilized and hatching, year t – 2,
γ_{t-2} – age-0 fish in-stream survival (emergence to September 1st), year t – 2,
δ_{t-2} – age-0 fish winter survival (September 2nd – May 15th), year t – 2,
ε_{t-1} – age-1 fish survival (May 16th – May 15th), year t – 1, and
θ_t – age-2 fish survival, year t.

It is assumed that a female that participates in the spawning run will deposit a clutch of eggs. The number of females in the spawning run is calculated as $f_t\widehat{N_t}$, where f_t is the proportion of females captured during the spawning run in year t, and $\widehat{N_t}$ is the estimated spawning run population corrected for imperfect detection (e.g., Paterson 2013). Length-specific fecundity, α_l, was estimated using data from Lund (1974) and Bishop (1971). Lund provided mean number of eggs and lengths by female length category; Bishop provided length and fecundity data from individuals. One of Bishop's observations (13th observation) was excluded as an outlier. Total fecundity in year t is then $F_t\alpha_l L_t$, where L_t is the length distribution of females in year t. Egg hatchability was taken from Lund's (1974)work in Elk Lake, 1972 and 1973. Hatchability varied from 0.04–0.12; the mean of these values (i.e., 0.08) was used for β.

Estimates of demographic rates were taken from published values for fish of similar life history, age, and size when empirical estimates were not otherwise available (Table 3). Maximum and mean survival rate values were obtained for model fitting. Age-2 survival, θ_t, was estimated using the upper confidence interval of annual survival for age-3 Red Rock Creek Arctic grayling (Patterson 2013). The upper confidence interval was selected because age-2 fish generally do not incur the risk of predation and physiological demands associated with spawning and, resultantly, likely have higher annual survival than age-3 fish. Annual survival of age-2 fish will also be estimated from ongoing research within Upper Lake using radio-marked individuals (M. Davis, pers. comm.). Age-1 annual survival, ε_{t-1}, and age-0 winter survival, δ_{t-2}, were calculated by averaging published survival estimates for fish of similar life history, age, or size. Published survival estimates were transformed, when necessary, to account for differences between time intervals of published estimates and parameters of the grayling models. Because no published estimates applicable to age-0 in-stream survival, γ_{t-2}, were found, we calculated this rate for all years with adequate data using equation 1 and the aforementioned age specific rates and solving for γ_{t-2}. Average age-0 in-stream survival was the average of the calculated rates among years and maximum age-0 in-stream survival was the highest annual value calculated.

Table 3. Demographic estimates used for testing competing models of grayling response to winter habitat, spawning habitat, non-native predation, and spring hydrology.

	Average survival rate (maximum survival rate) size range in mm; age range time period applicable to survival rate			
Species	γ_{t-2}	δ_{t-2}	ε_{t-1}	θ_t
Arctic grayling[1,2,3]	**0.014 (0.035)** 15-100; 0-90 d 90 days	**0.25 (0.48)** 100-150; 90 d -1 y .75 year	**0.44 (0.68)** 153-211; 1-2 y 1 year	**0.74 (0.87)** 263-340; 2-3 y 1 year
Bull trout[4]	--	0.23 (0.38) 121-170; 2 y 1 year	--	--
Chinook salmon[5]	--	0.16 (0.48) 61-115; 90 d- 1.2 y 0.95 year	--	--
Bull trout[6]	--	0.09 (0.60) 121-170; 2y 1 year	0.45 (0.85) 171-220; 3y 1 year	--
Brown trout[7]	--	0.26 (0.47) 120-175; 0.5-1 y .75 year	0.43 (0.50) 200-305; 1-3 y 1 year	--

[1]Katzman 1998; [2]Mogen 1996; [3]Paterson 2014; [4]Bowerman, T. and P. Budy 2012; [5]Achord, S., R. Zabel, and B. Sanford 2007; [6]Al-Chokhachy, R. and P. Budy 2008; [7]Dieterman, D.J. and R.J.H. Hoxmeier 2011.

Model Prediction and Parameter Estimation—Models representing competing hypotheses of system dynamics will predict grayling spawning population in year $t+1$ using population size in year t and 1) winter habitat conditions in years $t-2$ through t, 2) spawning habitat $t-2$, 3) non-native fish present winters $t-2$ and $t-1$, or 4) spring hydrologic conditions $t-2$, depending on which hypothesis a model represents. Maximum likelihood estimates of model parameters will be updated annually for prediction the subsequent year.

The data structure for fitting models is included in Appendix I. Names and definitions of imported and created variables are provided.

Spawning Habitat Model—The relative quality of spawning habitat was hypothesized to influence cohort strength by its influence on egg (β) and age-0 fish in-stream (γ) survival. Low per capita area of suitable spawning habitat would lead to low egg and age-0 fish in-stream survival due to increased intra-specific competition for available spawning habitats, resulting in increased use of low suitability or unsuitable spawning habitat with lower intrinsic rates of egg and age-0 fish in-stream survival. Although degradation of spawning habitat is caused by the same mechanism (sedimentation) that degrades habitat for older fish, survival rates are most likely to be directly influenced in ages that are unable to avoid degraded habitat (i.e., eggs and fry).

The definition of suitable spawning habitat follows Hubert et al.'s (1985) functional relationships between suitability and percent fines and gravels in spawning riffles, where ≤10% fines is considered suitable, 11–50% fines represent linearly declining suitability, and >50% is unsuitable (Figure 2). Conversely, ≥20% gravel and rubble is considered suitable with <20% representing a linearly declining suitability (Figure 3). Thus, suitable spawning habitat can be characterized by having ≤10% fines and ≥20% gravel and rubble.

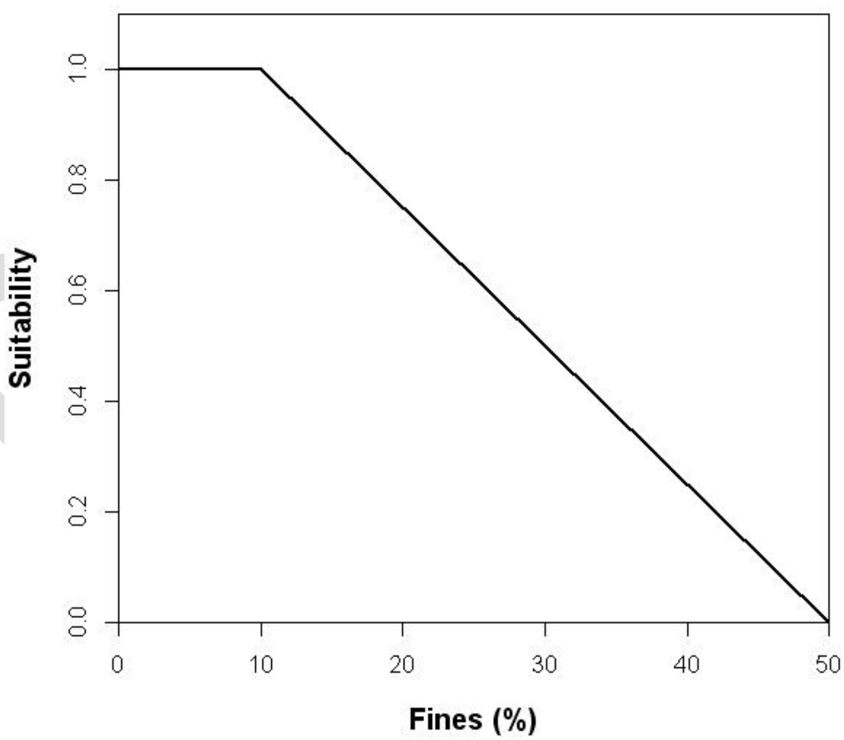

Figure 2. Predicted relationship between suitability of riverine Arctic grayling spawning habitat and percent fines in spawning areas and downstream riffles (from Hubert et al. 1985).

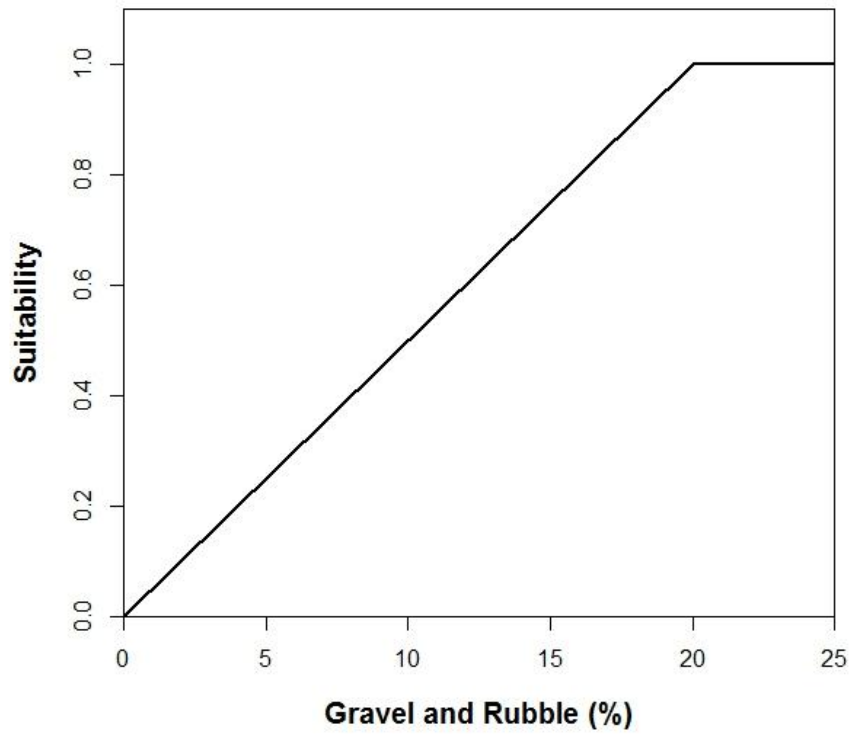

Figure 3. Predicted relationship between suitability of riverine Arctic grayling spawning habitat and percent gravel and rubble (1.0–20.0 cm) in spawning areas (from Hubert et al. 1985).

The suitability threshold provided by Hubert et al. (1985) predicts the proposed asymptotic relationship between spawning area and recruitment. For example, at low population and high area of suitable spawning habitat, individuals would presumably all utilize the most suitable areas, resulting in maximum egg and age-0 fish in-stream survival, and number of recruits per individual. Further increases in suitable spawning habitat would not result in greater per capita recruitment. However, if the population increased, and suitable spawning area per individual decreased, more individuals would spawn in less suitable habitats and an overall decrease in per capita recruitment would result as egg and age-0 fish in-stream survival declined.

Percent fines (particles < 2.8 mm) and gravel and rubble (8-180 mm) in riffles will be estimated annually using pebble count surveys. Each stream of interest was divided into reaches based on gross geomorphological characteristics and one or two representative sites were selected for sampling within each reach (Appendix II). At each sampling site, four separate consecutive riffles are sampled following MT DEQ TMDL Sediment Assessment Methods (in press). Cumulative percent fines are calculated for each sampled riffle.

Total area of suitable spawning habitat, A_t, is calculated and modeled considering 1) only habitat that has a suitability of 1.0 (i.e., ≤ 10% fines and ≥20% gravel and rubble) and 2) weighted suitability of habitat based on observed percent fines and gravel and rubble following Hubert et al. (1985; Figures 2 and 3).

Habitat area per stream with suitability of 1.0, A_{ts}, is riffle area per site with suitability = 1.0, divided by total site length, multiplied by reach length, summed across reaches within a stream (Equation 2).

$$\sum_{i=1}^{n} \frac{suitable\ riffle\ area\ (m^2)}{total\ site\ length\ (m)} \times reach\ length_i \tag{2}$$

Habitat area per stream with weighted suitability, A_{tw}, differs from A_{ts} in using the product of riffle suitability scores for percent fines and gravel and rubble estimated from the hypothesized suitability relationships of Hubert et al. (1985) instead of classifying riffle habitat as suitable (i.e., suitability = 1) or not (suitability <1).

Area of suitable habitat (A_t) will also be annually adjusted to account for the effects of beaver dams and fragmentation. Habitat backwatered by beaver dams becomes unsuitable for spawning for at least the life of the beaver dam and the number and location of beaver dams varies among years. Each stream will be annually surveyed and the total length of beaver dam backwaters will be subtracted from each reach length when calculating A_t. The effects of fragmentation can range from incrementally reducing the likelihood of passage past a given location depending on daily conditions to completely precluding passage for that year. If passage is completely prevented then the area of upstream spawning habitat is functionally zero. If the probability of upstream passage is reduced then the area of available habitat is similarly reduced. To correct for the effects of fragmentation the area of suitable spawning habitats upstream of a barrier that prevents passage (i.e., probability of upstream passage is 0.0) will not be included in calculation of A_t. Probability of passage at beaver dams will be estimated based on the results of a study in progress and annual assessment of relevant beaver dam characteristics within each reach each year during the peak spawning period. Calculation of A_t will be adjusted by multiplying the area of suitable habitat upstream of a beaver dam by the probability of passage at that dam. The effects of reduced passage probability will be cumulatively considered. For example, the calculated value of A_t upstream of three beaver dams would be multiplied by the probability of a fish passing all three dams.

Assuming species specific density dependence, the availability of suitable spawning habitat per fish, H_t ($m^2\ fish^{-1}$), is related to the area of suitable spawning habitat, A_t, and the number of spawning females, F_t

$$H_t = \frac{A_t}{F_t}. \tag{3}$$

Spawning habitat was related to the product of egg and age-0 fish in-stream survival, R_t, using a saturating function (i.e., Holling type-II functional response) by

$$R_t = \frac{aH_t}{b+H_t}. \quad (4)$$

The parameters *a* and *b* determine how survival of eggs and age-0 fish are related to spawning habitat conditions. Maximum survival is *a*, and *b* represents the value of suitable spawning habitat when survival is 50% of *a* (Hilborn and Mangel 1997).

The spawning habitat model for grayling population dynamics and observation error, linking recruitment to spawning habitat conditions, is:

$$N_{t+1} = N_t S_t + F_{t-2}\alpha_{t-2}R_{t-2}\delta_{t-2}\varepsilon_{t-1}\theta_t \quad (5)$$

$$N_{obs,t} = N_t V_t. \quad (6)$$

Adult grayling survival and total abundance year t, number of females year $t-2$, and length-specific fecundity $t-2$ are obtained from sampling. Age-0 winter (δ), age-1 annual (ε), and age-2 annual (θ) fish survival were taken from published estimates for similar-aged salmonids or estimated for this grayling population (Table 1) and assumed to be constant among years. The product of survival estimates resulted in a value of 0.082, i.e., ≈8% of age-0 fish that reach Upper Lake are predicted to survive through their second winter. There is only a single component to the likelihood for this model, adult grayling annual abundance estimates.

We used simulated data to explore the spawning habitat model. The area of available spawning habitat (ha) each year was randomly generated using a normal distribution with mean = 12 and standard deviation = 3 (*N*(12,3)). Survival of eggs and age-0 fish in-stream, R_t, and abundance of spawning grayling were subsequently calculated using the spawning habitat model and fixed demographic rates $\alpha = 8628$ eggs female^{-1}, $\delta = 0.25$, $\varepsilon = 0.44$, and $\theta = 0.74$ (see Table 1 for explanation of each parameter). Observation error for predicted grayling abundances was included, assuming $\sigma_v = 0.01$. Maximum survival of eggs and age-0 fish in-stream, *a*, was 0.10 for simulations. Two values for *b*, the relative importance suitable spawning habitat, were used in simulations (*n* = 1000) to compare scenarios where spawning habitat minimally influences R_t (*b* = 0.10; Figure 4), or was a primary driver (*b* = 15; Figure 5).

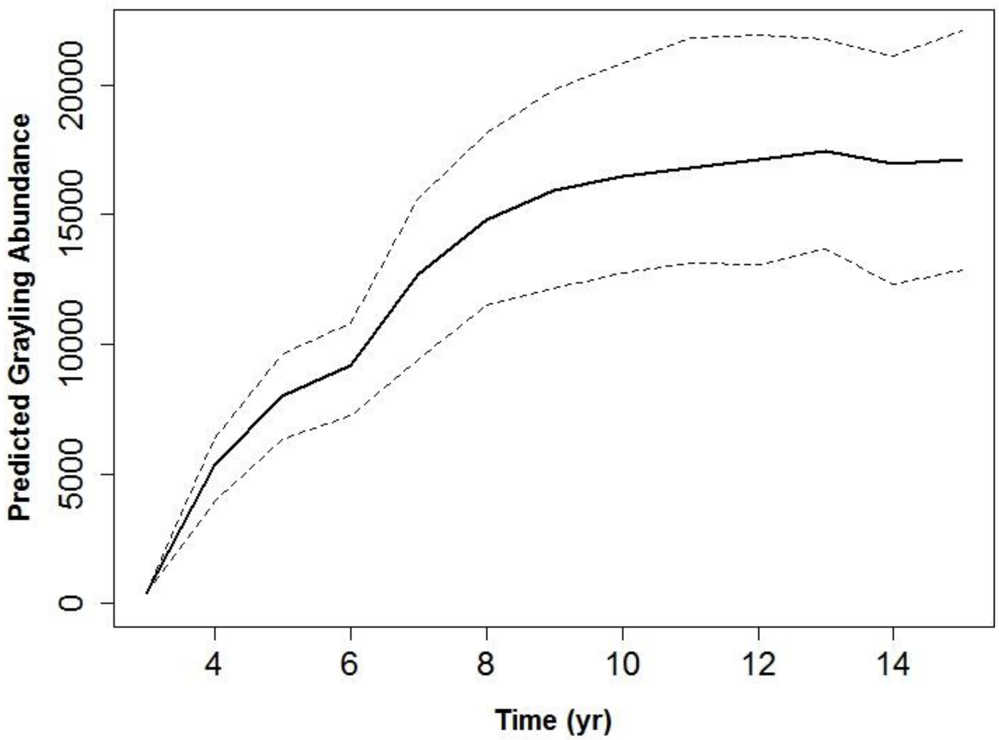

Figure 4. Simulation results (n = 1000) for spawning habitat model (see text) with an initial starting population of 400 grayling projected for 15 years. Maximum survival of grayling eggs and age-0 fish in-stream, a, is 0.10, and b, the value of suitable spawning habitat to an individual when survival is 50% of a, is 0.1. Dotted lines represent the 90% confidence interval for the simulations.

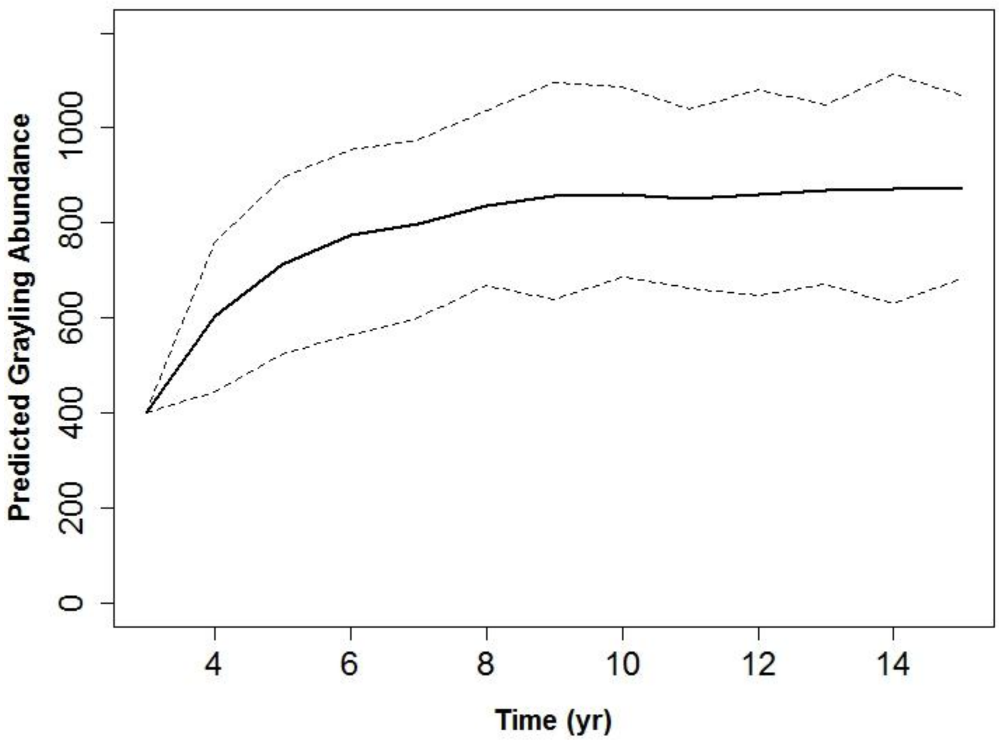

Figure 5. Simulation results (n = 1000) for spawning habitat model (see text) with an initial starting population of 400 grayling projected for 15 years. Maximum survival of grayling eggs and age-0 fish in-stream, a, is 0.10, and b, the value of suitable spawning habitat to an individual when survival is 50% of a, is 15. Dotted lines represent the 90% confidence interval for the simulations.

Predation Model—Non-native Yellowstone cutthroat trout (trout) were hypothesized to reduce survival of a grayling cohort prior to age-2, i.e., reduced age-0 through age-1 survival, via predation. To use the same model structure as the other hypotheses outlined above we considered grayling mortality (i.e., 1 - survival) instead of survival. This allows grayling mortality to increase rapidly with increasing trout abundance up to a threshold at which mortality approaches an asymptote. Mortality of cohort *i* from hatching to age-1, Z_i $(1 - \gamma_{t-2}\delta_{t-2}\varepsilon_{t-1})$, was asymptotically related to the mean abundance of adult trout during the cohort's first two years. For example, mortality up to age-2 of a grayling cohort that hatched year *t* would be related to the mean abundance of adult trout in years $t + 1$ and $t + 2$, C_t as

$$Z_t = \frac{aC_t}{b+C_t}. \quad (7)$$

This results in a balance equation, relating grayling mortality to trout abundance, with the following form:

$$N_{t+1} = N_t S_t + F_{t-2}\alpha_{t-2}\beta_{t-2}Z_i\theta_t. \quad (8)$$

Adult trout abundance will be annually estimated during spawning in Red Rock Creek by adding the number of fish 1) harvested by anglers, 2) removed at the fish weir, and 3) remaining in the system. Adult trout will be experimentally removed from Red Rock Creek from 2013-2017 by angler harvest and culling fish at the weir to generate an adequately broad range of trout abundances to test this hypothesis. Number of fish harvested by anglers will be estimated from catch cards corrected for non-reporting (Appendix III). Most trout encountered at the weir will be enumerated, euthanized, and transported to area food pantries. The number of trout in the spawning run not removed at the weir or by angling will be estimated annually. Approximately 100 trout captured at the weir will be marked with a uniquely numbered tag (i.e., t-bar anchor Floy tag) and released upstream of the weir. The number of trout, marked and unmarked, encountered during electrofishing will be recorded and used to estimate detection probability (i.e., capture efficiency). The number of trout encountered during electrofishing will then be corrected for imperfect detection to estimate the number of trout not removed from the system. This number will be added to the number of trout removed at the weir and by angler harvest to estimate the total number of trout in a spawning run. Because trout have a lower likelihood of being detected below the weir due to asynchronous timing of their spawning run and electrofishing surveys the number of fish remaining in the system will be underestimated. Therefore, the aforementioned overall abundance estimates represent an index of trout abundance that is less than actual abundance.

The aforementioned enumeration of C_t likely provides a minimum estimate of the number of adult trout a given grayling cohort hatched year t was subjected to in years $t+1$ and$t+2$. It is possible that some adult trout present in the Upper Lake system do not ascend Red Rock Creek for spawning or complete spawning and return to Upper Lake prior to attempts to quantify their abundance. It is likely that some adult trout that were present during times when a given cohort of grayling was subject to predation die prior to the spawning period. However, C_t is likely proportional to the number of adult trout present each year.

The predation model does not differentiate between competition and predation, but will quantify the response of grayling to trout population reduction. Evidence for niche overlap between grayling and trout, where the potential for competition exists, occurs when trout are <450 mm in total length (USFWS upubl. data). The management action being undertaken, Yellowstone cutthroat trout removal during spawning, is primarily removing larger (>450 mm) fish, which not only precludes a direct test of competition but also does not allow estimation of trout of the size class that potentially compete with grayling. Lastly, evidence for bottom-up regulation, e.g., low condition factor for either species observed during spawning, is lacking.

Winter Habitat Model—The influence of winter habitat on the grayling population would likely manifest itself as reduced survival of all-age grayling during years with widespread hypoxic conditions in Upper Red Rock Lake (e.g., Greenbank 1945). If the response of different age-class fish to winter habitat conditions is proportionally constant, e.g., poor winter conditions halve fish survival across all age classes, it is possible to estimate the relationship between all-age survival and winter conditions.

The temporal and spatial extent of hypoxia in Upper Red Rock Lake is influenced by several factors, including 1) lake level (i.e., depth), 2) area, 3) trophic status, 4) ice thickness, 5) and snow cover (Mathias and Barica 1980, Gangloff 1996, Fang and Stefan 1997, Fang et al. 2004). Measuring dissolved oxygen levels throughout Upper Red Rock Lake during winter is the most direct means to determine the extent of hypoxic conditions. Models to retrospectively predict winter dissolved oxygen conditions in Upper Red Rock Lake are available (e.g., Fang and Stefan 1997, Fang et al. 2004), which would allow use of historic data.

The influence of winter habitat conditions on grayling will be quantified based on the amount of winter habitat available between December and March, the period of hypoxic conditions experienced during the winter of 1994–1995 (Gangloff 1996). Available winter habitat is defined as the area (ha) of water in Upper Red Rock Lake from December to March with ≥1.8 ppm dissolved oxygen and ≥ 20 cm in depth (Feldmeth and Eriksen 1978, Gangloff 1996). Assuming species specific density dependence, available winter habitat per fish, W_t (ha fish^{-1}), is related to the area of suitable winter habitat, A_t, and the number of fish, $N_{w,t}$, that entered the winter period.

$$W_t = \frac{A_t}{N_{w,t}} \qquad (9)$$

The estimated number of spawning fish in Red Rock Creek in year *t* will be used as an index for $N_{w,t}$. Winter habitat will be related to the proportional change in all-age grayling survival using a saturating function (i.e., Holling type-II functional response) by

$$P_t = \frac{aW_t}{b+W_t}. \qquad (10)$$

The parameters *a* and *b* determine how the proportional reduction in maximum grayling survival is related to winter habitat conditions. Maximum proportional reduction in grayling survival is *a*, and *b* represents the value of suitable winter habitat to an individual when the proportional change in survival is 50% of *a* (Hilborn and Mangel 1997). For example, if no proportional reduction to survival occurs *a* = 1, i.e., grayling survive at their maximum age-class rates. To assess if the influence of available winter habitat is density independent, A_t will be substituted for W_t in Equation 10. Figure 6 shows a hypothetical situation where *a* = 1, *b* = 10, and W_t varies from 10 to 100 ha fish^{-1}.

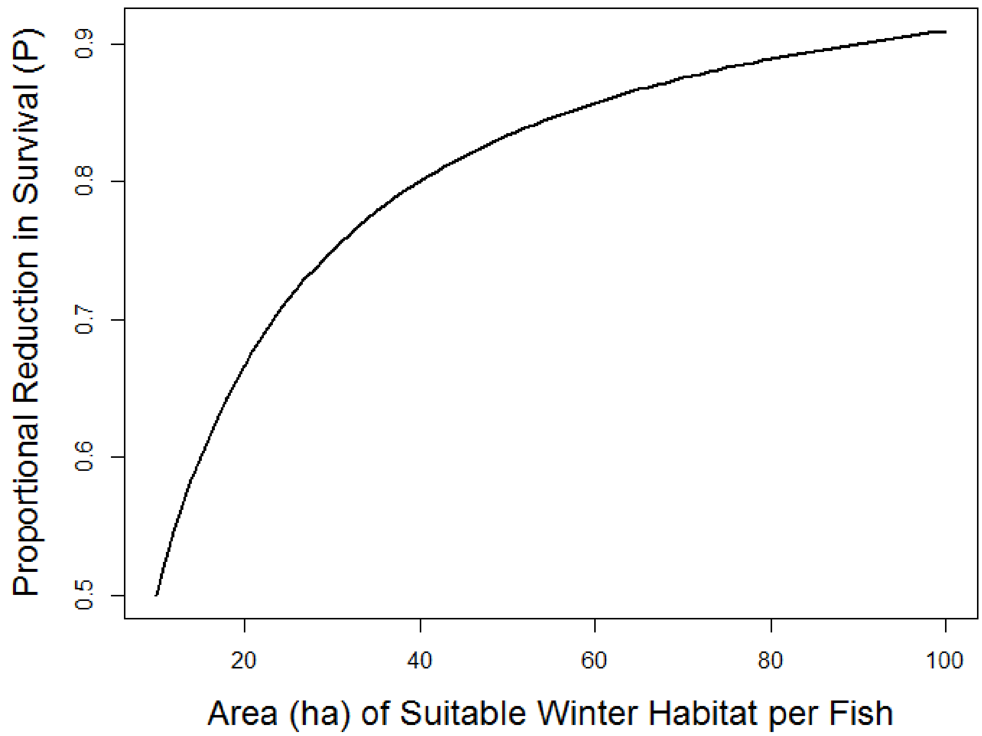

Figure 6. Hypothetical relationship between the proportional reduction in maximum grayling survival and the area of suitable winter habitat per fish in Upper Red Rock Lake based on a Holling type-II functional response.

The winter habitat model for grayling population dynamics and observation error, linking survival to winter habitat conditions, would then be:

$$N_{t+1} = N_t S_t P_t + F_{t-2} \alpha_{t-2} Y_{t-2} (\delta_{t-2} P_{t-2})(\varepsilon_{t-1} P_{t-1})(\theta_t P_t), \quad (11)$$

$$N_{obs,t} = N_t V_t. \quad (12)$$

The number of adult fish surviving from year t to year $t+1$ is the product of the number of adults in year t, maximum annual survival (S_t), and the proportional reduction of survival due to winter habitat conditions (P_t). The number of potential recruits in year t is the number of age-2 fish, which is the product of the number of females $t-2$, length-specific fecundity $t-2$, the probability of an egg laid in year $t-2$ surviving until its first winter, Y_{t-2}, (the combined probabilities of egg (β) and age-0 stream (γ) survival), and maximum survival of age-0 winter (δ), and age-1 (ε) survival for cohort i multiplied by the estimated proportional influence of winter habitat on survival for each respective winter. The number of recruits in year $t+1$ is the product of the cohort in time t, second year survival (θ_t), and P_t. Substituting in demographic rates assumed fixed and constant (described above), gives the following equation for the winter habitat model

$$N_{t+1} = N_t * 0.74P_t + F_{t-2}\alpha_{t-2} * 0.0112 * (0.48P_{t-2})(0.68P_{t-1})(0.87P_t). \quad (13)$$

There are two components to the likelihood for this model, adult grayling annual abundance and survival. For the latter, apparent survival (φ) estimates for 1993–1996 (0.41, 95% CI = 0.24–0.66) and 2010–2013 (0.63, 95% CI = 0.53–0.74) are available (Paterson 2013). Estimates of φ will be obtained annually using marked individuals.

We used simulated data to explore the potential utility of the winter habitat model. The area of available winter habitat each year was calculated as

$$A_t = U_t m Ar \quad (14)$$

where U_t was a uniformly distributed random variable between 0 and 1, *m* was the number of winter months (i.e., 4), and *Ar* was the total area of Upper Red Rock Lake (1198 ha). Annual survival and population was subsequently calculated using the winter habitat model. We also included observation error for predicted grayling abundances (i.e., *V*, see above), assuming σ_v = 0.01. The relative importance of *b*, the value of suitable winter habitat to an individual when survival is 50% of *a* (Hilborn and Mangel 1997) can be easily demonstrated using the simulations. For example, we can compare simulations from two time series that differ only in the value of *b*; one with a low value (0.1; Figures 7 and 8), and a second with a greater value (2.0; Figures 9 and 10). It quickly becomes obvious that as the relative 'value' of winter habitat increases so does the influence of winter conditions on grayling population.

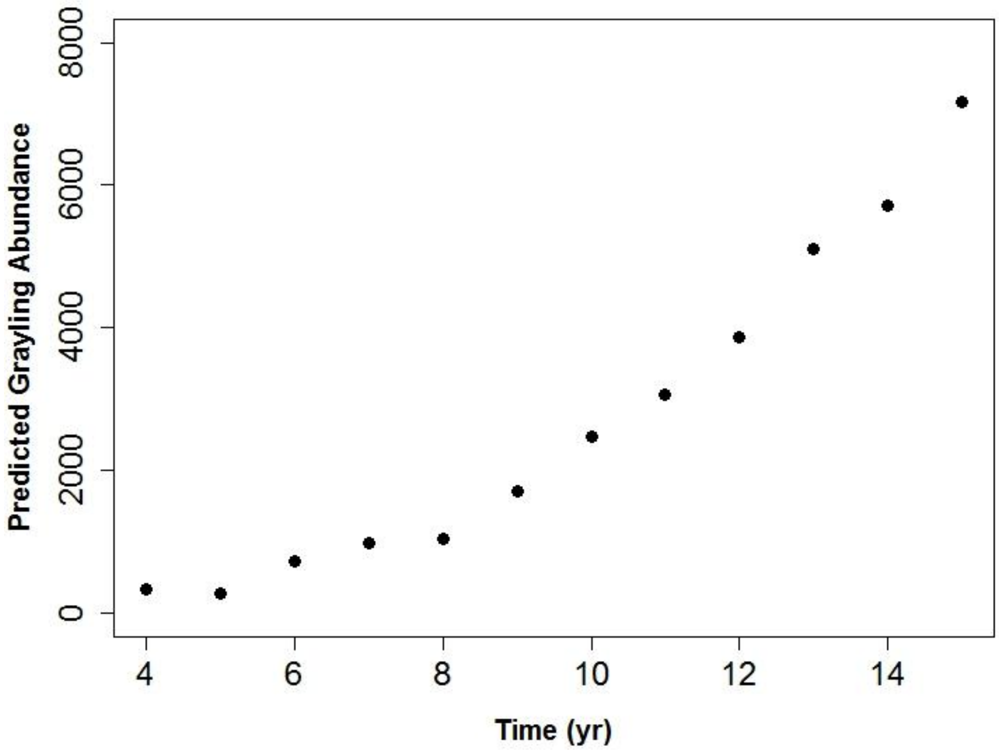

Figure 7. Simulation example for winter habitat model (see text) with an initial starting population of 400 grayling projected for 15 years. Maximum grayling survival, *a*, is 1, and b, the value of suitable winter habitat to an individual when survival is 50% of *a*, is 0.1.

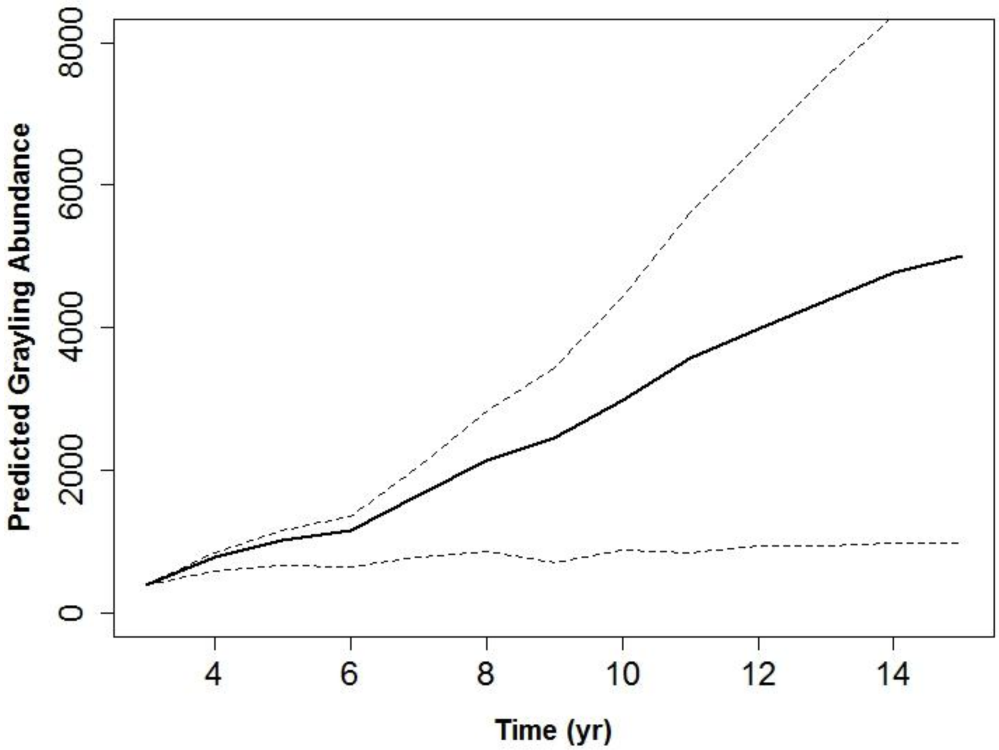

Figure 8. Simulation results (n = 1000) for winter habitat model (see text) with an initial starting population of 400 grayling projected for 15 years. Maximum grayling survival, a, is 1, and b, the value of suitable winter habitat to an individual when survival is 50% of a, is 0.1. Dotted lines represent the 90% confidence interval for the simulations.

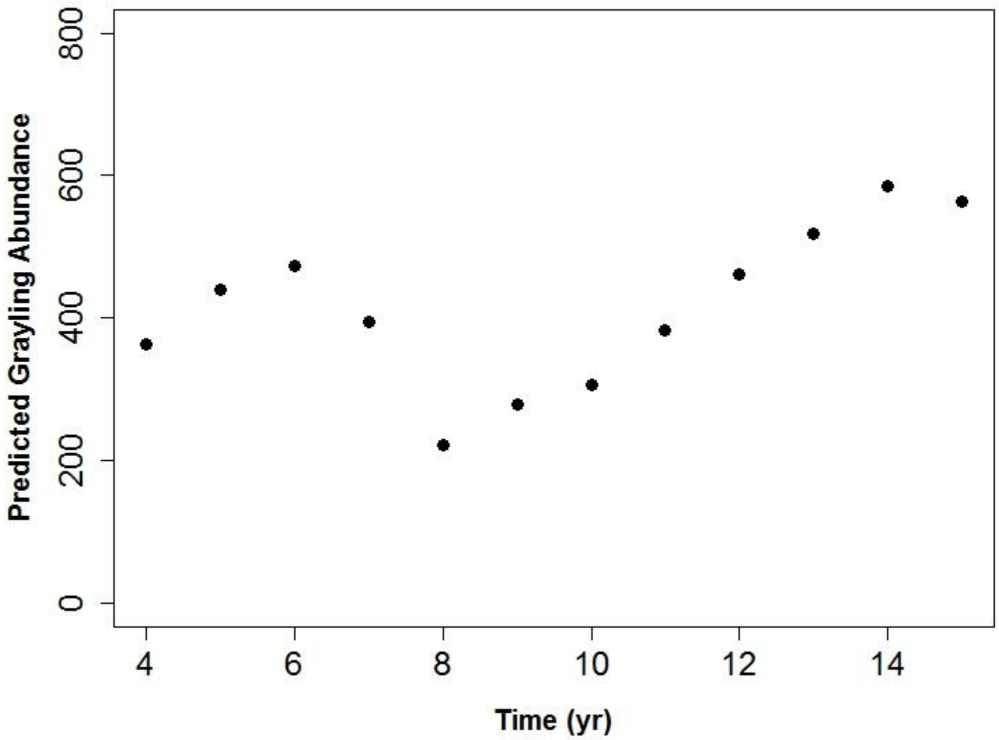

Figure 9. Simulation example for winter habitat model (see text) with an initial starting population of 400 grayling projected for 15 years. Maximum grayling survival, *a*, is 1.0, and b, the value of suitable winter habitat to an individual when survival is 50% of *a*, is 2.0. Simulation years 6–8 demonstrate the influence of a series of winters with low habitat suitability on grayling population.

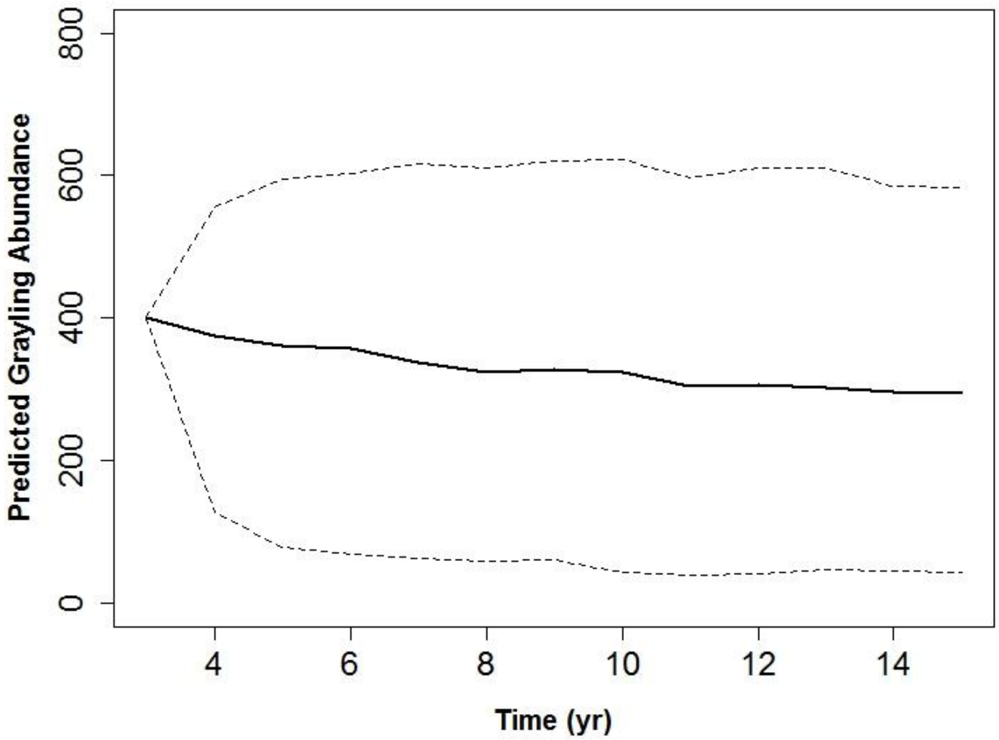

Figure 10. Simulation results (n = 1000) for winter habitat model (see text) with an initial starting population of 400 grayling projected for 15 years. Maximum grayling survival, a, is 1.0, and b, the value of suitable winter habitat to an individual when survival is 50% of a, is 2.0. Dotted lines represent the 90% confidence interval for the simulations.

Spring Hydrology Models—Ambient conditions during egg deposition and incubation, and fry emergence and development, may be a primary driver of grayling year class strength. Influential conditions are likely a combination of density independent variables related to stream temperature and discharge. Year class strength and growth in grayling is negatively correlated with high flows or flooding and positively correlated with warm temperatures during critical periods of fry development (Clark 1992, Deegan et al. 1999). Thus, years with low, stable flows and warm temperatures would be expected to produce strong cohorts and years with high or flashy flows and cold temperatures would be expected to produce weak cohorts. We defined the “critical period,” during which variability of flow and temperature will likely have the largest influence on cohort strength, to range from spawning through early fry development. Based on hypothesized effects of spring hydrology this period can be divided into two ontogenetic phases: 1) egg incubation and 2) early fry development. Survival of incubating eggs can be negatively affected by hydrologic scenarios that mobilize riffle substrate, thereby crushing or transporting eggs to less favorable habitats, or depositing sediment on gravels, which may smother incubating eggs. Temperature is also a potential driver during this phase of the critical period because it sets its duration; during cool years eggs take longer to hatch, which increases the amount of time they are susceptible to unfavorable hydrologic scenarios. Following hatching grayling fry have limited mobility and typically aggregate in areas of low velocity along stream margins. The occurrence of hydrologic scenarios that potentially redistribute and strand grayling in off-channel habitats may reduce year class strength. Temperature similarly affects fry by driving development rate; at warmer temperatures grayling fry would grow faster and be expected to better negotiate high or flashy flows. Thus, spring hydrology models were developed to both examine general effects of cool, high versus warm, low stream flows over the entire critical period and more specific flow and temperature metrics during each phase.

Timing and duration of the critical period will be empirically determined each year. The beginning of the critical period is defined as the day of peak spawning activity. Peak spawning will be estimated using the observed relationship between grayling spawning and stream discharge and temperature. Peak spawning is believed to occur seven days after the peak capture day at the fish weir, coinciding with grayling beginning to be captured in the downstream segment of the weir (M. Jaeger, unpubl. data). Duration of incubation is 188 degree days following peak spawning date, which is the upper 95% confidence interval of mean time to hatch and swim up of fry in Centennial Valley remote site incubators (MFWP and USFWS unpubl. data). Fry emergence, i.e., *peak spawning* + 188 *degree days*, will be estimated annually using stream temperature data collected via thermographs. The period of early fry development is defined as the five weeks immediately following fry emergence. This duration was based on empirical observations of fry development in the Centennial Valley and the period over which streamflows influenced cohort strength of other grayling populations (Clark 1992).

Four spring hydrology models were created to test predictions associated with hypothesized spring hydrology drivers of cohort strength. Spring hydrology variables calculated during the defined critical period include: 1) Mean daily stream discharge (*mdd*); 2), Cumulative degree days from peak emergence to 5 weeks post-emergence (*cdd*); 3) Count of days with *mdd* above bankfull discharge (*cbf*); 4) Count of days with *mdd* above 67% of bankfull discharge (*c67bf*; 95.6 cfs); and 5) a synthetic variable that quantifies temperature and discharge conditions along a single axis from cold, high flow springs to warm, low flow springs (*pca*). Stream discharge greater than 67% of bankfull was selected as it identifies a threshold above which bed load larger than sand and granules are mobilized (Mueller et al. 2005), which could disperse grayling eggs and reduce the likelihood they will hatch. Mean daily discharge (*mdd*) and bankfull discharge for Red Rock Creek were estimated using data from the USGS gauging station 06006000 located on Red Rock Creek upstream of Elk Lake Road (1994-2014) and weekly readings by Refuge staff (1994-1996) were interpolated to provide daily data. Recurrence interval was estimated as the inverse exceed ance probability ($^{rank}/_{n+1}$) using ranked annual peak flow data (1998–2014 excluding 1997). Bankfull discharge was estimated as 142.7 cfs using a return interval of 1.5 years (Dunne and Leopold 1978), which is most representative of high elevation snowmelt dominated systems (Lawlor 2004). Temperature data will be collected annually using thermographs deployed in Red Rock Creek.

Survival of grayling eggs and age-0 fish within the natal stream were hypothesized to reach a maximum at intermediate values of mean daily discharge, with low survival during extreme low or high water years. The Ricker function (Ricker 1954, Bolker 2008) was used to relate survival to mean daily discharge, where

$$R = a \cdot (mdd - 20) \cdot e^{-b \cdot (mdd-20)}. \tag{15}$$

The location parameter was set at a value 62.5% of the minimum mean daily discharge observed 1994–2013 (32 cfs), which results in *R* = 0 at 20 cfs. The spring hydrology model for grayling population dynamics and observation error, linking recruitment to mean daily discharge, takes the same form as the spawning habitat model (Equations 5 and 6)

$$N_{t+1} = N_t S_t + F_{t-2} \alpha_{t-2} R_{t-2} \delta_{t-2} \varepsilon_{t-1} \theta_t \tag{16}$$

$$N_{obs,t} = N_t V_t. \tag{17}$$

Using data from 1994–2013, excluding 1997 (Figure 11), a fixed spring hydrology window (15 May – 31 July), and mean grayling abundance during 1994–1995 as an estimate for 1996 grayling abundance, we fit the above model to obtain estimates of *a*, *b*, and *R* (Figure 12). Estimates were 0.0035 and 0.0807 for *a* and *b*, respectively. Maximum survival of grayling eggs and fry was 0.0156, attained at a mean daily discharge of 32 cfs.

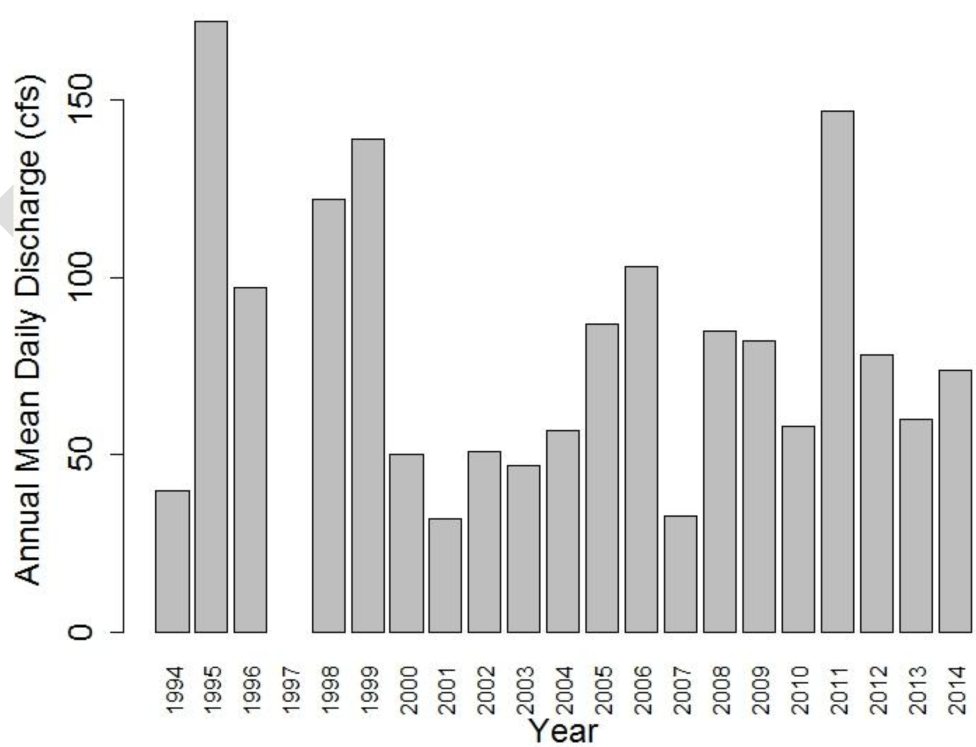

Figure 11. Annual mean daily discharge in cubic feet second^{-1} (cfs) for Red Rock Creek 15 May – 31 July, 1994–2014, as measured at the US Geological Survey gaging station 06006000 upstream of Elk Lake Road.

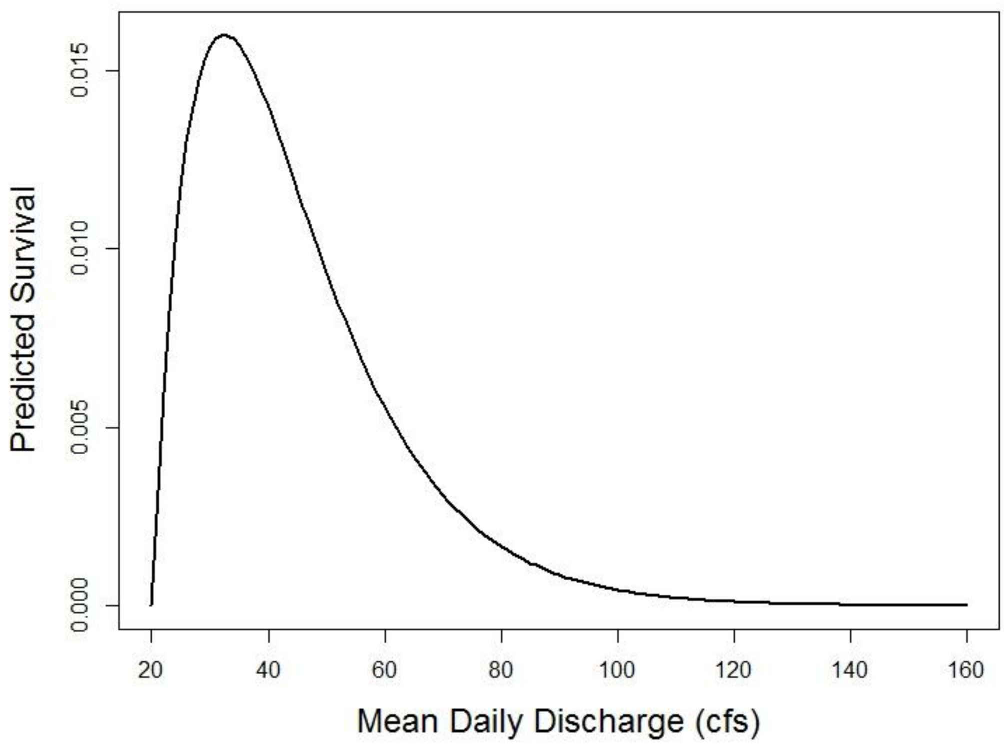

Figure 12. Predicted relationship between egg and age-0 fry survival post-emergence until reaching Upper Red Rock Lake (R) and Red Rock Creek mean daily discharge (cfs).

The second spring hydrology model tests the hypothesis that grayling egg and age-0 in-stream survival would be most influenced by extreme runoff events. A negative exponential relationship between R and discharge days above bankfull discharge was predicted based on this hypothesis, where

$$R = ae^{-b\cdot(dbf)}. \tag{18}$$

We similarly fit the spring hydrology model above to existing data using this hypothesized functional form of the relationship between *dbf* and *R*. Most years with *dbf* values above zero occurred during 1995–1999, which coincided with only a single year with an estimate of grayling abundance (Figure 13). This led to a predicted relationship between *dbf* and *R* with a steep slope, i.e., *R* quickly declined to near zero at *dbf* values greater than zero. Estimated values of *a* and *b* were 0.0124 and 1.627, respectively. Maximum survival was estimated as 0.0124 at 0 *dbf*, declining to a survival rate of <10 individuals per one million eggs surviving (R = 7.75×10^{-6}) at 8 *dbf* (Figure 14).

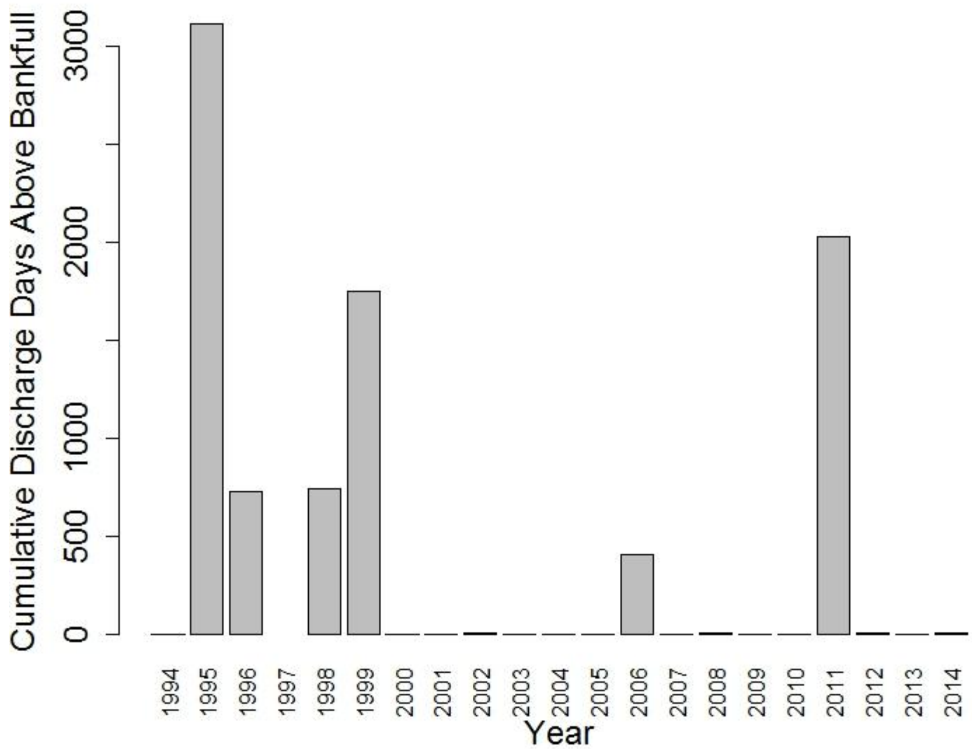

Figure 13. Cumulative discharge days above bankfull for Red Rock Creek 15 May – 31 July, 1994–2014. Bankfull discharge was estimated as 141 cfs (see text above).

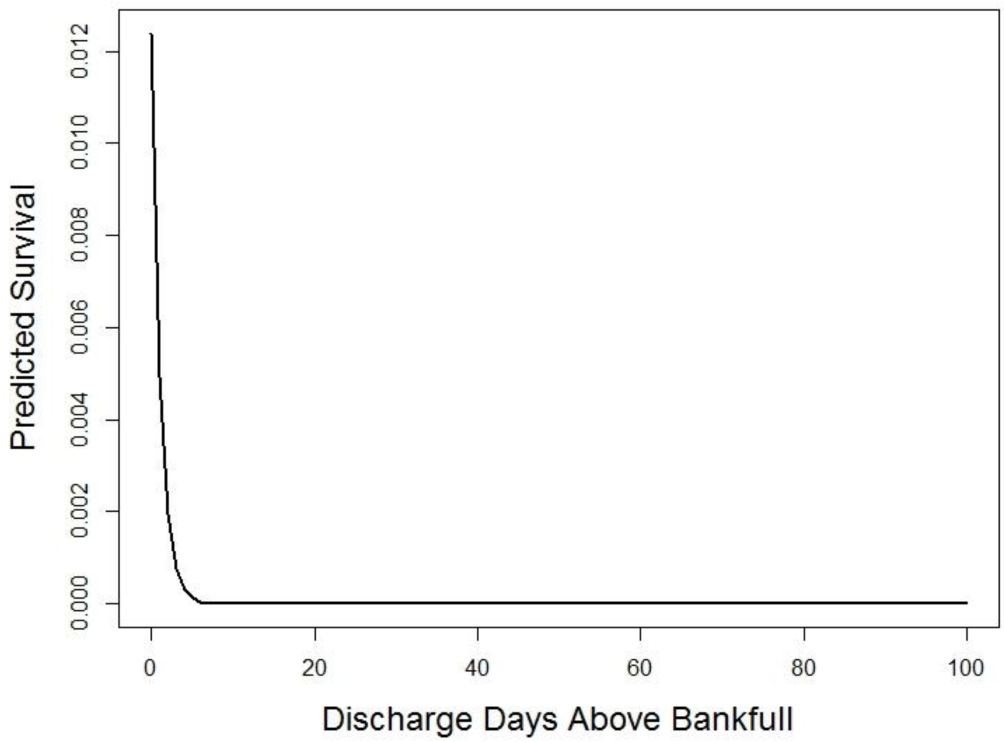

Figure 14. Predicted relationship between egg and age-0 fry survival post-emergence until reaching Upper Red Rock Lake (*R*) and Red Rock Creek discharge days above bankfull (*dbf*).

The third spring hydrology model tests the hypothesis that grayling egg and age-0 in-stream survival is most influenced by cumulative degree days. The relationship between survival and cumulative degree days was hypothesized to be linear across the range of values expected to be experienced, where

$$R = a \cdot cdd + b. \tag{19}$$

The stream temperature time series available for fitting the *cdd* model was limited to seven years, most of which did not coincide with available estimates of grayling abundance (Figure 15). This precluded fitting this model to existing data at this time. Additional legacy temperature data may be available and if located may allow model fitting with the existing time series of grayling abundances.

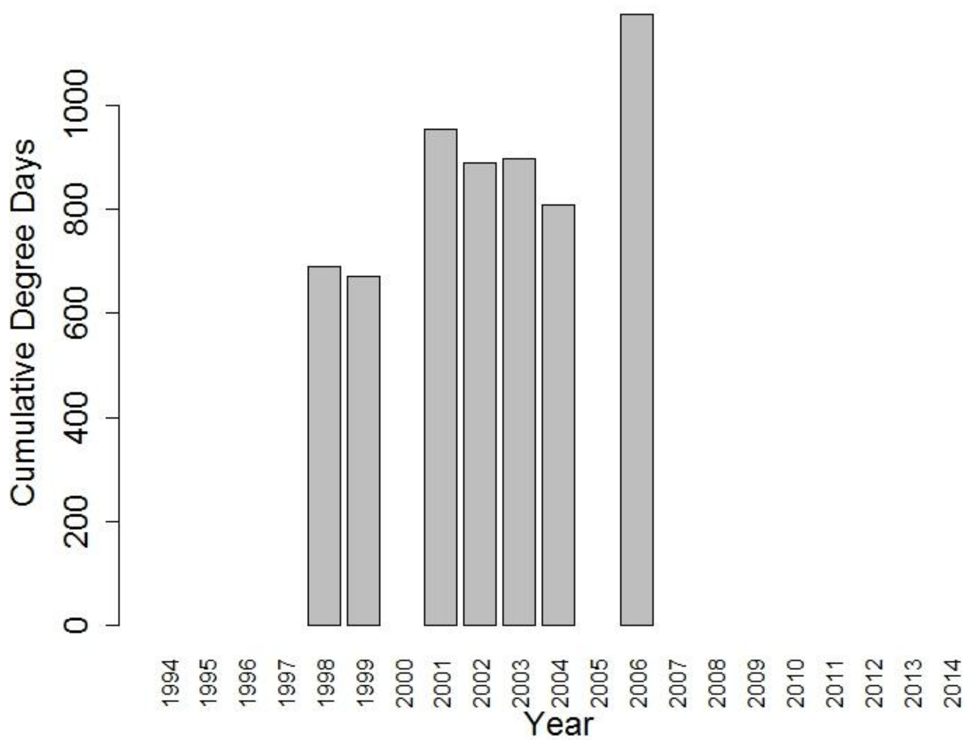

Figure 15. Cumulative degree days for Red Rock Creek 15 May – 31 July, 1994–2014.

The final spring hydrology model incorporates a synthetic variable that combines stream discharge and temperature conditions. This allows us to test the hypothesis that grayling cohort strength is maximal during warm, dry springs when grayling development rates are high and the likelihood of egg sedimentation or fry stranding events low. We combined mean daily water temperature, mean daily discharge, and whether or not mean daily discharge exceeded 67% of bankfull (i.e., 0 or 1). The latter two variables are highly correlated (ρ = 0.806). Similar to the mean daily discharge model, we chose the Ricker function (Ricker 1954, Bolker 2008) to relate survival to the synthetic variable, where

$$R = a \cdot (mdd + 1) \cdot e^{-b \cdot (mdd+1)}. \tag{20}$$

The location parameter was set at the 15th percentile value representing cold, high flow springs based on 1994–2013 data, which results in *R* = 0 at *pca* = -1.

Null Population Model—A discrete-time logistic growth equation was included as a 'null' model for grayling for the purpose of comparison to more highly parameterized hypothesis-specific models. If the null model is able to best predict grayling abundance it indicates fundamental flaws in either the structure or underlying hypotheses of the other candidate models. The null model was based on corrected counts beginning with 1994, where

$$N_{t+1} = N_t + rN_t\left(1 - \frac{N_t}{K}\right). \tag{21}$$

In this equation, N_t is the population at time *t*, *r* is the intrinsic rate of population growth, and *K* is carrying capacity. The model is deterministic, i.e., no stochastic variation is included. There are two primary sources of variation that can be considered, process error and observation error. Process error is the result of uncertainty in how a population varies in space and time due to birth and death processes. Importantly, process error propagates through time in time-series data, with gaps in that data (i.e., missing years) significantly increasing the difficulty in estimating process error (Hilborn and Mangel 1997). Observation error is variation due to imperfect enumeration of the population of interest, i.e., our inability to accurately estimate abundance. Observation error does not propagate through time. If we assume observation error is log-normally distributed (commonly done for the logistic equation), observation error is

$$N_{obs,t} = N_t V, \tag{22}$$

$$V = exp\left(Z\sigma_v - \frac{\sigma_v^2}{2}\right), \tag{23}$$

where *Z* is normally distributed with a mean of zero and a standard deviation of 1, and the standard deviation of the observation uncertainty is σ_V (Hilborn and Mangel 1997). To calculate maximum-likelihood estimates of *r* and *K* assuming observation error only, we first calculate the deviation between the observed and true (predicted from the deterministic logistic growth equation) values of population size. This is accomplished by substituting equation 3 into equation 2 and solving for *Z* ($\sigma_v = 1$). The deviation in year *t*, D_t, is the annual realization of the random variable *Z*, so substituting D_t for *Z* after solving for Z gives us

$$D_t = \log\left(N_{obs,t}\right) - \log(N_t) + \frac{\sigma_{V^2}}{2}. \tag{24}$$

We then find the most likely set of parameter values, *r* and *K*, given our data, as the set of values that maximize the summed log-likelihoods of D_t.

The logistic growth model was fit using grayling count data from 1994–2013 corrected for imperfect detection (Paterson 2013). Initial starting value, N_0, was set equal to the 1994 estimate (i.e., 407 grayling). Estimated grayling population growth rate, *r*, and carrying capacity, *K*, during 1994–2013 was 0.20 and 1366, respectively (Figure 16).

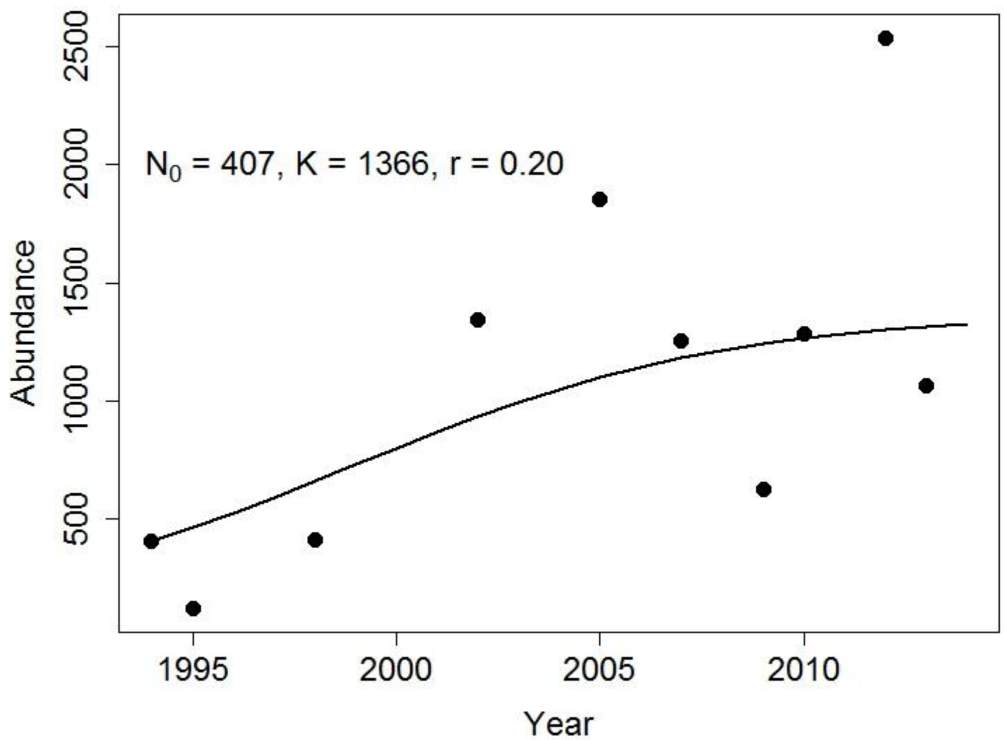

Figure 16. Discrete-time logistic population growth for Arctic grayling, 1994–2013. Data are from the Red Rock Creek fish weir operated near the Elk Lake Road crossing. Data are bias corrected abundance estimates (Paterson 2013). Starting values for *r* and *K* were 0.3 and 700, respectively.

<u>LOWER VALLEY HYPOTHESIS TEST EVALUATION</u>

Models of System Dynamics

Dewatering continues to be a primary threat to grayling persistence for some CV streams, specifically Long and West creeks. Physical habitat, which is a function of the interrelationships between flood plain connectivity, riparian health, efficient and contextually appropriate channel dimensions, a naturalized hydrograph, temperature regime, and sediment input, is also limited in these streams. The principal management approach that is being undertaken to address these threats is a Candidate Conservation Agreement with Assurances (CCAA) for Centennial Valley Arctic grayling (Appendix III). This agreement is intended to comprehensively address the aforementioned flow and habitat issues and result in increased grayling abundances in each stream. As such, it provides another opportunity to learn by taking the AM approach described by this plan. However, because these threats are inter-related and being simultaneously addressed by the CCAA it is not possible to individually assess and compare their relative influence on the grayling population. Rather, their cumulative effect on hypothesized population drivers (i.e., low stream flows, spawning habitat suitability, fragmentation, etc.) will be evaluated in the context of this plan by developing models to test hypotheses regarding the relative effect of the following three factors: 1) adult habitat, 2) spawning habitat, and 3) overwinter habitat.

Less biological knowledge of the grayling population that uses the Lower Valley and logistical difficulties of sampling it also necessitate use of a different response variable and more basic models. While the Upper Valley models explicitly linked population drivers to limiting factors in the form of age specific demographic rates (Table 1) this level of resolution is not available in the Lower Valley, even though the same relationships are anticipated. Hypothesized limiting factors in the Lower Valley will be more coarsely directly related to a genetic metric of population abundance using multiple linear regression models. The response variable for Lower Valley models is the effective number of breeders (Nb) that produced a given year's cohort. It is expected that Nb is correlated with census population size and provides an indication of how the CCAA influences the grayling population of interest. Nb will be evaluated each year using pooled samples collected in the Red Rock River watershed between Lower Red Rock Lake and Lima Dam. Although the specific time period Nb is relevant differs among models, annual estimation of this parameter over life of the AM Plan will allow for direct comparison among cohorts of spawners and discrimination among hypotheses. While this approach will decrease the sensitivity of models to changes in hypothesized limiting factors among years it will still allow detection of meaningful changes in abundance through time and the ability to discriminate among the potential limiting factors that caused them. As such, systemic knowledge will be gained through an ecological experiment and the AM approach remains an opportunity to learn from ongoing work and most efficiently achieve broader CV grayling population goals.

Adult Habitat Model – The adult habitat model will consider the effect low stream flow and high temperatures have on adult grayling each spring and summer (March 1 – September 30). Number of effective breeders that produced the cohort at time t+1, Nb_{t+1}, will be predicted by the cumulative number of days each stream's discharge is below the lower inflection point, L_t, the cumulative number of days each stream's discharge is between the upper and lower inflection points, U_t , and the cumulative number of days or hours each stream's temperature exceeds 73°F, T_t as follows:

$$Nb_{t+1} = \beta_0 + \beta_1 L_t + \beta_2 U_t + \beta_3 T_t. \tag{25}$$

Spawning Habitat Model - The spawning habitat model will consider the effect stream flow and available spawning habitat have during the putative critical period (April 15 to July 1) on grayling that were spawned that year. Explanatory variables will be the hectares of available spawning habitat and the cumulative number of days each stream experiences critically low discharges. Hectares of available suitable spawning substrate, A_{tw}, will be estimated as described in the Upper Valley spawning habitat model. Cumulative days of low discharge, F_t, is defined as the total number of days that Lower Valley streams are below their CCAA target values (Table 5). The response variable will be the number of effective breeders that produced the cohort at time t+3, $Nb_{t+3,}$ which will be the first time a cohort produced at time t will be effectively sampled. This model will be structured as:

$$Nb_{t+3} = \beta_0 + \beta_1 A_{tw} + \beta_2 F_t + \beta_3 T_t. \tag{26}$$

Winter Habitat Model - The winter habitat model will relate adult the grayling population to Lima Reservoir elevation on January 1 of the previous winter, E_t, as follows:

$$Nb_{t+1} = \beta_0 + \beta_1 E_t. \tag{27}$$

Finally, a null population model will be fit as described above with the following structure:

$$Nb_{t+1} = Nb_t + rNb_t\left(1 - \frac{Nb_t}{K}\right). \tag{28}$$

These models will be compared each year as described above to evaluate population drivers and the overall effectiveness of the CCAA.

Table 5. Streamflow targets for each stream or river including targets for the April 15 through July 15 spawning/rearing period as well as the remainder of the year (base flow). The targets for April 15 and July 1 are transitional targets between periods and are the average of the adjacent targets. Targets differ depending on streamflow conditions (i.e. dry and normal).

	Dry								
	Corral	Antelope	Red Rock Cre	Tom	Odell	Long	West	Red Rock River	Period
March	1.5	0.4	15.0	1.4	11.0	2.2	2.8	32.8	Base Flow
April 1	1.5	0.4	15.0	1.4	11.0	2.2	2.8	32.8	Base Flow
April 15	3.4	1.5	21.5	7.2	16.4	4.8	6.6	77.9	Spawning
May	5.2	2.5	27.9	13.0	21.8	7.5	10.3	123.0	Spawning
June	5.2	2.5	27.9	13.0	21.8	7.5	10.3	123.0	Spawning
July 1	3.4	1.5	21.5	7.2	16.4	4.8	6.6	77.9	Spawning
July 15	1.5	0.4	15.0	1.4	11.0	2.2	2.8	32.8	Base Flow
August	1.5	0.4	15.0	1.4	11.0	2.2	2.8	32.8	Base Flow
September	1.5	0.4	15.0	1.4	11.0	2.2	2.8	32.8	Base Flow
	Normal								
	Corral	Antelope	Red Rock Cre	Tom	Odell	Long	West	Red Rock River	Period
March	6.0	1.3	15.0	1.4	11.0	3.4	5.9	55.0	Base Flow
April 1	6.0	1.3	15.0	1.4	11.0	3.4	5.9	55.0	Base Flow
April 15	7.2	2.6	28.1	10.6	21.1	7.0	10.2	114.0	Spawning
May	8.3	3.9	41.1	19.8	31.2	10.5	14.5	173.0	Spawning
June	8.3	3.9	41.1	19.8	31.2	10.5	14.5	173.0	Spawning
July 1	7.2	2.6	28.1	10.6	21.1	7.0	10.2	114.0	Spawning
July 15	6.0	1.3	15.0	1.4	11.0	3.4	5.9	55.0	Base Flow
August	6.0	1.3	15.0	1.4	11.0	3.4	5.9	55.0	Base Flow
September	6.0	1.3	15.0	1.4	11.0	3.4	5.9	55.0	Base Flow

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APPENDIX I

DATA STRUCTURE

Fish Population Data—Data beginning with 1962 fish weir counts are imported as dataframe 'fish.all.years'. The early data are only used for graphically displaying counts through time. Data are subset based on year starting with 1994 as dataframe 'grayling'. These are the data used in fitting models for the AMP using the following variables:

Grayling abundance (grayling$grayling). Grayling data after 1993 are corrected for detection probability. Estimates for 2005, 2007, 2009 were calculated as the number of grayling captured during electrofishing divided by the mean efficiency rate (0.075).

Cutthroat trout abundance (grayling$cutt). Cutthroat data are a combination of the number of fish 1) harvested by anglers, 2) removed at the fish weir, and 3) remaining in the system.

Grayling apparent survival (ϕ, grayling$phi). Currently from Terrill's thesis; constant phi during 2 periods (1993-1996 = 0.41, 2011-2013 = 0.63). Survival interval is from trap session current year to trap session subsequent year (i.e., survival for May 2010 to May 2011 is in the 2010 record). We will estimate phi annually within the workflow process once full implementation is achieved.

Age-3 grayling (grayling$p3YO). Percent of Arctic grayling captured electrofishing that are age-3 fish (i.e., new recruits). Age-3 fish were those between 12.9" (329 mm) and 14.9" (379 mm) based on Mogen (1996). Additional age-length data are being collected through scale-reading efforts currently underway. This information will be added to the existing workflow process once it is finalized.

Mean grayling female length (grayling$mn.fl). Mean annual female length (cm) based on individuals captured on the MFWP's Red Rock Creek electrofishing trend section.

Cutthroat trout removed (grayling$cutt.rm). Estimate of cutthroat trout removed via the fish weir and angler harvest.

Variables calculated and appended to the grayling dataframe include:

Time (grayling$time). Time variable (in years) with 1994 as year 1.

Grayling recruits (grayling$est3YO). Estimated number of recruits for a given year calculated by multiplying proportion age-3 grayling observed during electrofishing on the Red Rock Creek trend section by estimated abundance corrected for detection probability.

Grayling females *t* -3 (grayling$ft3). Estimated number of females three years prior for a given year calculated as half of the estimated abundance corrected for detection probability.

Mean grayling female length *t* -3 (grayling$mn.flt3). Mean female length three years prior for a given year.

Abiotic and Habitat Data—Variables describing spawning habitat, winter habitat, and spring hydrology are calculated in the workflow process and added to the grayling dataframe. These include:

Mean daily stream discharge (grayling$mdd). Annual critical period mean daily stream discharge for Red Rock Creek estimated based on USGS gaging station (06006000) daily discharge data, 1997 to current. Estimates from 1994–1996 were from manual flow readings available in Refuge files.

Days above bankfull (grayling$cbf). Annual critical period count of days with mean daily stream discharge ≥ bankfull (142.7 cfs).

Days above 67% bankfull (grayling$c67bf). Annual critical period count of days with mean daily stream discharge ≥ 67% bankfull (95.6 cfs).

Discharge data to calculate the above variables need to be downloaded annually for 1 April – 1 September from http://nwis.waterdata.usgs.gov/nwis/dv?cb_00060=on&format=html&site_no=06006000&referred_module=sw&period=&begin_date=2013-05-15&end_date=2013-07-31. Annual updates need to be appended to 'Red_Rock_Cr_discharge_data.csv' located in the project's AnnualReport folder.

Cumulative degree days (grayling$cdd). Annual cumulative degree days from peak grayling emergence to 5 weeks post-emergence. Red Rock Creek temperature data were collected by the USFWS Management Assistance Office via Onset HOBO dataloggers starting in 1998 (excluding part of 2001, and 2006, 2007, 2009, and 2014). Data from other CV streams are variously available. These data are housed in a database maintained by M. Jaeger, J. Warren, and J. Dullum.

Synthetic spring hydrology variable (grayling$pca). Synthetic variable combining *mdd*, *c67bf*, and *cdd* using principal components analysis to create a variable that describes cold, high flow springs to warm, low flow springs along a single axis.

Per capita suitable spawning habitat (grayling$Ats). Per capita suitable spawning habitat within Red Rock Creek based on binary suitability (i.e., suitable or not suitable).

Per capita suitable spawning habitat (grayling$Atw). Per capita suitable spawning habitat within Red Rock Creek based on weighted habitat suitability.

Per capita suitable winter habitat (grayling$Wt). Per capita suitable winter habitat within Upper Red Rock Lake.

APPENDIX II

SPAWNING HABITAT SAMPLING REACHES

Pebble count sample reaches and number of sites within each reach used to quantify suitability and area of spawning habitat.

Stream	Reach	# Sites	Total riffles	Comments
Red Rock Cr.	Hellroaring Cr.	1	4	TNC Section
Red Rock Cr.	Huntsman	2	8	1 upper and 1 lower site
Red Rock Cr.	U.S. Corral Cr.	2	8	State land above Corral Cr; 1 upper and 1 lower site
Red Rock Cr.	D.S. Corral Cr.	2	8	State land below Corral Cr; 1 upper and 1 lower site
Red Rock Cr.	Antelope Beaver Dams	2	8	1 site starting below beaver dams and 1 site above or in between dams in backwater
Red Rock Cr.	U.S. Elk Lake Rd.	2	8	Refuge land above Elk Lake Rd.; 1 upper and 1 lower site
Red Rock Cr.	D.S. Elk Lake Rd. & U.S. Battle Cr.	2	8	Refuge land below Elk Lake Rd.; 1 upper and 1 lower site
Red Rock Cr.	D.S. Battle Cr.	1	4	Refuge land below Elk Lake Rd.; 1 upper and 1 lower site
Elk Springs Cr.	Picnic Cr.	1	4	Picnic Cr. Between Widgeon and Culver ponds
Elk Springs Cr.	U.S. McDonald	1	4	Upstream of McDonald Pond
Elk Springs Cr.	McDonald	1	4	In bed of McDonald Pond
Elk Springs Cr.	D.S. McDonald	1	4	Between McDonald Pond and Elk Lake Rd.
Elk Springs Cr.	Below Road and beaver pond	1	4	Below Elk Lake Rd.
O’dell Cr.	Upper	1	4	Above South Valley Rd.
O’dell Cr.	Middle	1	4	Between S. Valley and “Sparrow Slough” roads (sec 24)
O’dell Cr.	Lower	1	4	Below “Sparrow Sl. Rd” (Sec 14)

APPENDIX III.

Annual estimates of angler harvest of hybrid Yellowstone cutthroat trout (YCT) in Red Rock Creek are required by models developed in the Centennial Valley Arctic Grayling Adaptive Management Plan. The goals of this survey were to provide annual estimates of:

1. The number of YCT harvested by anglers
2. Angler catch per effort of YCT
3. Distribution of angler effort up and down stream of the Elk Lake Road

A complemented survey over the duration of the spring angling season using 1) catch cards and 2) an access point survey was used to minimize bias and maximize accuracy of the aforementioned estimates. This survey was prepared using information referenced from Angler Survey Methods (Pollock et al. 1994) and Recreational Angler Survey Methods (Jones and Pollock 2012) *in* Fisheries Techniques (Zale et al. 2012).

Catch Cards: Catch cards are generally considered to be an off-site sampling method because they contain angler reported data and survey agents do not have to be present at a fishery to distribute or recover them. The advantages of these types of surveys are that they are inexpensive, simple to administer relative to all other methods, and continuously sample the fishery (i.e., catch cards are available to anglers at all hours of all days of the fishing season). The disadvantages of these types of surveys are that there are typically large biases associated with nonreporting, untruthful reports of catch, misunderstanding of questions, and misrepresentation of the angling population because of different likelihoods of responding contingent on the relative avidity of anglers.

Catch cards were used as part of this survey because of the simplicity of the fishery (one stream with a single primary access point where angling occurs over a short duration) and the information we require (number of YCT harvested). We anticipate that the primary source of bias will be nonreporting. Nonreporting rate will be independently and directly estimated by an access point survey as described below and will allow for correction of catch and harvest estimates reported on catch cards. In years when nonreporting rate was not adequately estimated, reported catch and harvest rates will be corrected using averaged nonreporting rate estimates from other years.

One of the primary sources of bias in all types of angler surveys is related to poor question structure and diction. This is especially true of open-ended questions, which we were included on our catch cards. The questions on the catch cards were simple, direct, and only pertained to information we required. Our catch cards contained the following questions:

1. **Date: ______ (month) / _______ (day) / 2014**
2. **Total number of cutthroat trout caught:_____________**
3. **Number of cutthroat trout harvested:_____________**

4. **Number of hours you were angling: ______________**

5. **Were you primarily fishing (circle one) DOWNSTREAM or UPSTREAM of the Elk Lake Road Bridge?**

The catch card portion of the survey occurred as follows:

- Catch cards were made available for the duration of the angling season at the Elk Lake Road bridge over Red Rock Creek and likely secondary access sites (i.e., the old bridge site on the road to Culver Pond).
- Pencils or pens were provided for anglers to complete catch cards.
- Clearly visible signage was strategically placed at the selected access site(s) that stated: "**Every angler must complete a survey card immediately following fishing each day**."
- An "iron warden" or some other type of deposit box was provided at each selected access site for anglers to submit completed surveys.
- Catch cards were retrieved daily and put in an envelope or file with the date written on it.
- Access sites were checked daily to ensure that signage was present and an adequate number of catch cards and pencils were available.

Access Point Survey: Access point surveys and other types of on-site methods have more accuracy and less bias than other approaches because harvest is directly observed by trained clerks. The primary disadvantage of these types of surveys is the expense associated with conducting them. Because of the narrow temporal and spatial scope of the Red Rock Creek cutthroat trout fishery a single access point can be surveyed without introducing meaningful bias.

The access point survey was conducted to estimate under or nonreporting rates of catch cards by providing an independent estimate of angler effort, total catch, and number of YCT harvested by sub-sampling during the angling season. The sampling design was structured to survey the highest proportion of total angling effort possible while taking into account likely variation among types of days. A stratified random sampling design was used to select days to conduct the access point survey. The strata were weekdays and weekends. At minimum, one weekday and one weekend day was randomly selected each week of the angling season for the access point survey. If additional sampling was possible it occurred in a manner that coincided with the highest amount of angler effort (i.e., selection of a weekend day rather than a weekday). Similarly, additional randomly selected days or effort was added to coincide with observed increases in angling effort during the season.

The access point survey occurred at the junction of the South Valley and Elk Lake roads and away from the primary parking and catch card distribution area. Because nonreporting rate of catch cards was estimated as part of the access point survey the access point survey was physically and psychologically separated from the catch card survey; anglers were not lead to believe that the access point survey in any way replaced their obligation to complete catch cards. A creel clerk was stationed at this location for the entire angling day during each day that was selected for sampling. Because it was unlikely that any anglers completed angling early in the morning surveys began around 9 am but continued until sunset. The creel clerk placed signs visible by vehicles approaching this intersection from all directions that indicated "**All anglers must stop**." The creel clerk recorded the same information as that requested by the catch cards for each angler:

1. **Date: ______ (month) / _______ (day) / 2014**
2. **Total number of cutthroat trout caught:_____________**
3. **Number of cutthroat trout harvested:_____________**
4. **Number of hours you were angling: ______________**
5. **Were you primarily fishing (circle one) DOWNSTREAM or UPSTREAM of the Elk Lake Road Bridge?**

Duration of surveys: The entire angling season was surveyed as described above during most years (access surveys were not conducted during some years). The start of the angling season varied among years based on snow and road conditions and usually began sometime after April 1st. The end of the angling season coincided with the FWP closure beginning on May 15th. As such, the maximum duration of the complemented survey was about 6 weeks (April 1 to May 15) and included a minimum of 13 days (7 week days and 6 weekend days) of access point surveys each year. The catch cards were deployed every day throughout the angling season.

Analysis of data: Total effort, catch, and harvest of YCT will be calculated from catch cards by adding those values submitted for all catch cards over the entire angling season (equations 19.4 and 19.5 in Jones and Pollock 2012) and dividing by their respective reporting rates (1-nonreporting rate). Daily reporting rate of total effort, catch, and harvest was determined by dividing the effort, catch, and harvest reported on catch cards by that observed and reported during the access point surveys on days where both types of surveys occur. Mean reporting rates were determined by averaging all daily rates. Data were analyzed to determine if there are statistically significant differences in reporting rates among strata (weekdays versus weekends) and the results were applied accordingly. Angler harvest of YCT in 2013 and 2014 were adjusted by using the nonreporting rates calculated in subsequent years.

Total effort, catch, and harvest of YCT were independently estimated using the access point survey data and applying equations 19.6 and 19.7 in Jones and Pollock (2012).

The final annual estimate of effort, catch, and harvest of YCT were determined by averaging the estimates of these parameters provided by each of the survey types. Mean annual catch per effort was determined by dividing each angler's catch by their effort and averaging those over the angling season for each survey type. Data pertaining to fishing location (above or below Elk Lake Road) was analyzed to determine whether it is meaningful to spatially segregate description of catch per effort.

1) Removal of non-native fish at the Red Rock Creek fish trap
   i) Number and removals
   ii) Estimate of the number of cutthroats that made it past the weir
      (1) Estimating the number of cutthroats that made it past the trap will allow us to estimate 1) the total number of cutthroats in the spawning population, 2) proportion removed (i.e. capture efficiency, $E = c/N$, where c is the number of captured fish and N is the total spawning population size), 3) and the number that spawned upstream of the trap. We can most easily estimate this using a two-sample Lincoln-Peterson estimator, with the first sample being fish caught, marked, and released upstream of the weir (n_1) and the second sample being fish caught during electrofishing (n_2). The number of fish recaptured during the second period is m_2. A bias-corrected Lincoln-Peterson estimator for population size is

$$\widehat{N} = \frac{(n_1 + 1)(n_2 + 1)}{(m_2 + 1)} - 1,$$

with an approximately unbiased variance estimate

$$\widehat{var} = \frac{(n_1 + 1)(n_2 + 1)(n_1 - m_2)(n_2 - m_2)}{(m_2 + 1)^2(m_2 + 2)}$$

from Seber (1970).

      (2) Due to violations of assumptions with the approach above, we'll also use the 1) number of cutthroats captured in the downstream trap up to the point when electrofishing begins and 2) the number of cutthroats enumerated during electrofishing to estimate the number of cutthroats that spawned above the trap.